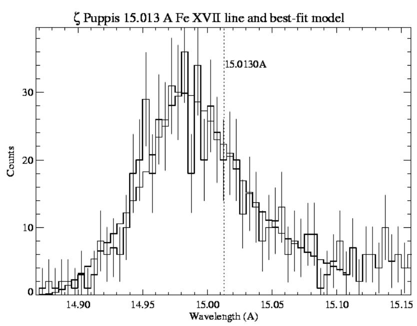
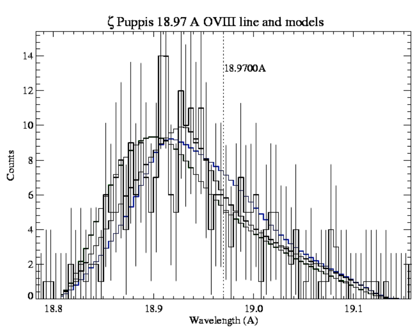
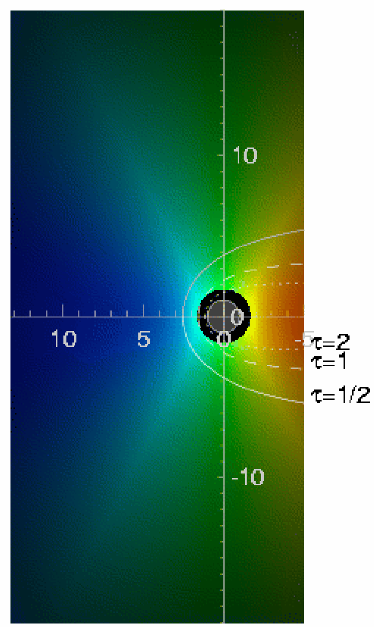
High-Resolution Spectroscopy of OB Stars:

Using Emission Line Profiles to Constrain Wind Kinematics, Geometry, and Opacity







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much of this work was performed by Swarthmore seniors Roban Kramer and Stephanie Tonnesen

Outline

Introduction: the context of hot star X-rays

What do the observations look like?

What trends emerge, and how can the properties of the individual stars and of the trends among lines and among stars be explained by the physical effects we expect might be present?

- ζ Pup: wind x-rays, but less absorption than expected
- ζ Ori and δ Ori: similar situation, very little wind absorption; but wind-shock parameters are otherwise satisfactory
- Magnetic OB stars are a different story: θ^1 Ori C, τ Sco, γ Cas
- And so are normal B stars: β Cru, ε CMa

Binaries and other types of hot stars

Prospects for the future

Types of Hot Stars

Normal (effectively single)

- Young
- Main sequence and evolved

WR stars

Extreme stars (η Carina, γ Cas?)

Colliding wind binaries

Questions we’d like to address with high-resolution X-ray spectroscopy

What’s the nature of wind instabilites and shocks in normal hot stars? Can this (class of) model(s) work?

What role do magnetic fields play in hot stars and their X-ray emission? (e.g. do B stars have coronae? How can young hot stars be so hot and bright in X-rays? How can hot stars with extreme X-ray properties be understood?)

What is the correct shock physics and radiation hydrodynamics at the interface between colliding winds? (e.g. how important is radiative breaking? Hydrodynamic instabilities?)

Diagnostics and Physical Properties

We're talking about thermal, collisional/coronal, equilibrium, optically thin plasmas here…*probably*

Temperatures and overall emission levels: DEMs

Densities: line ratios…but also source location via *f*/*i*

Abundances: line ratios and line-to-continuum ratios

Local absorption: globally and within individual lines

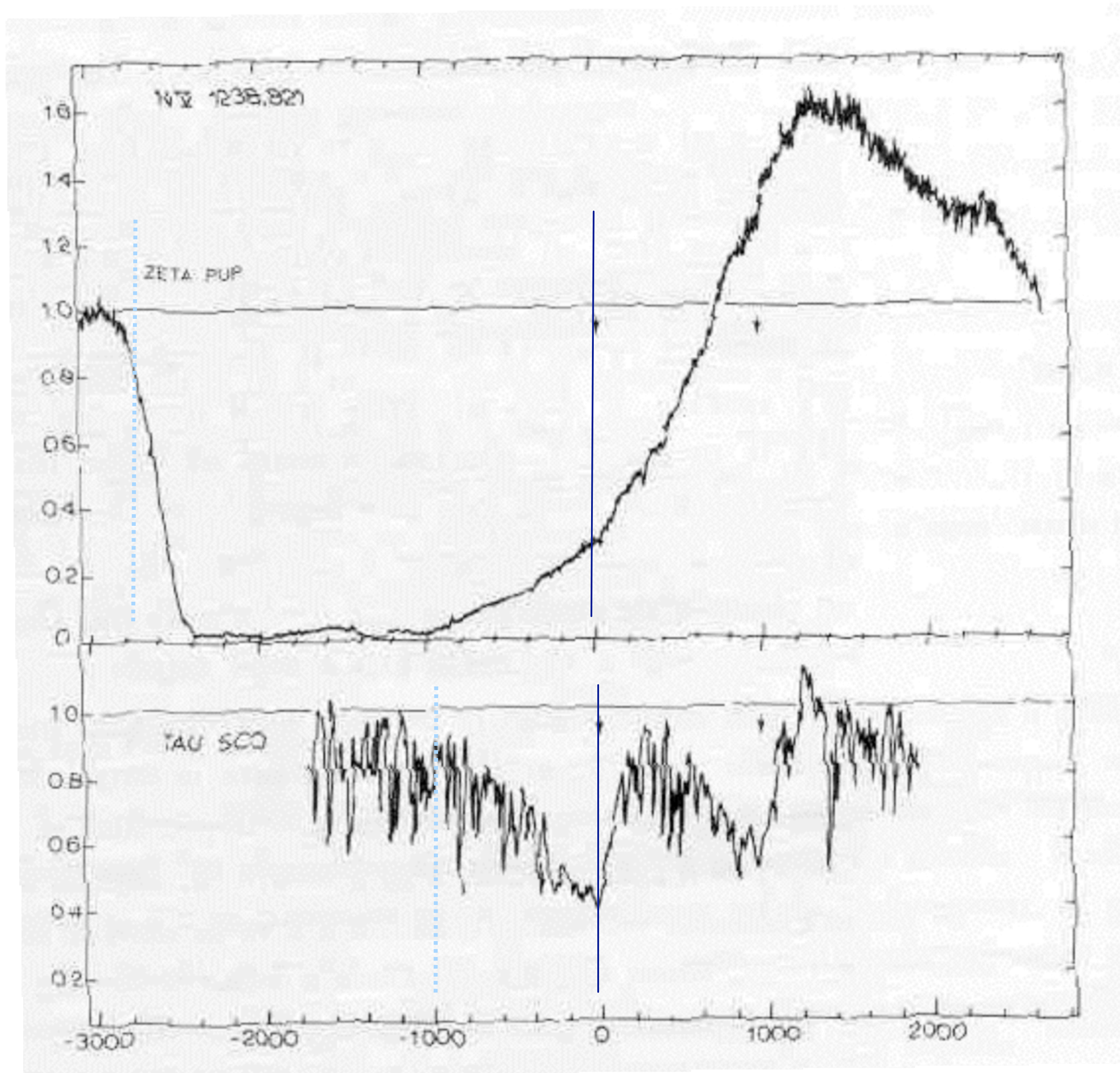
Signatures of photoionization: fluorescence

Kinematics: line broadening and profile shapes

OB stars have massive, radiation-driven winds

Observed P Cygni profiles in two hot stars: **ζ Pup** (O4, $10^6\ L_{sun}$) and **τ Sco** (B0 V, 50,000 L_{sun})

Steady-state theory is very successful at explaining the time-average properties of hot-star winds

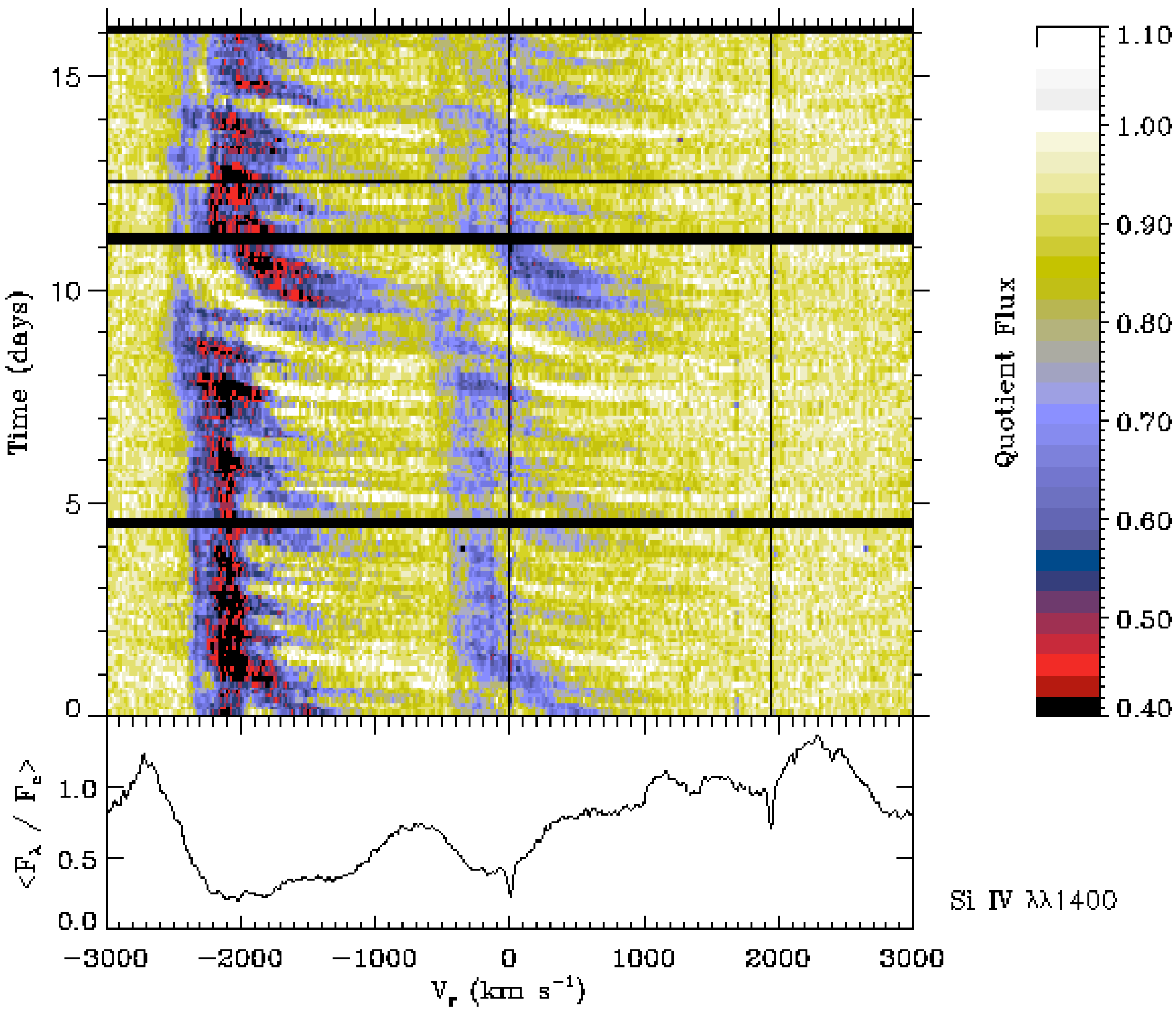


But, hot star winds are not steady-state: They display lots of time variability.

16 days of UV spectra of ζ Pup.

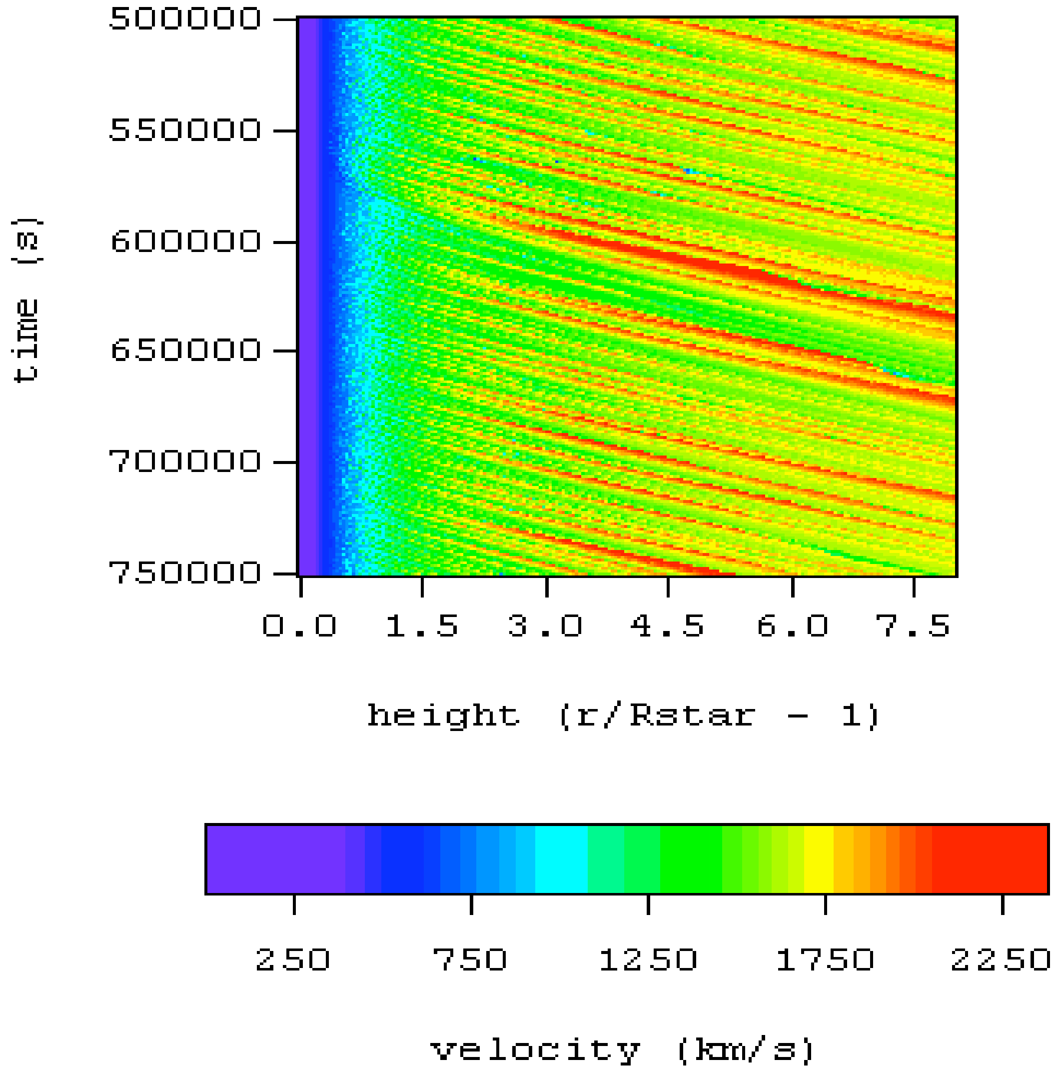
The color plot is the ratio of each spectrum to the mean spectrum (bottom).

Cyclical and stochastic variability is seen in most hot stars' winds

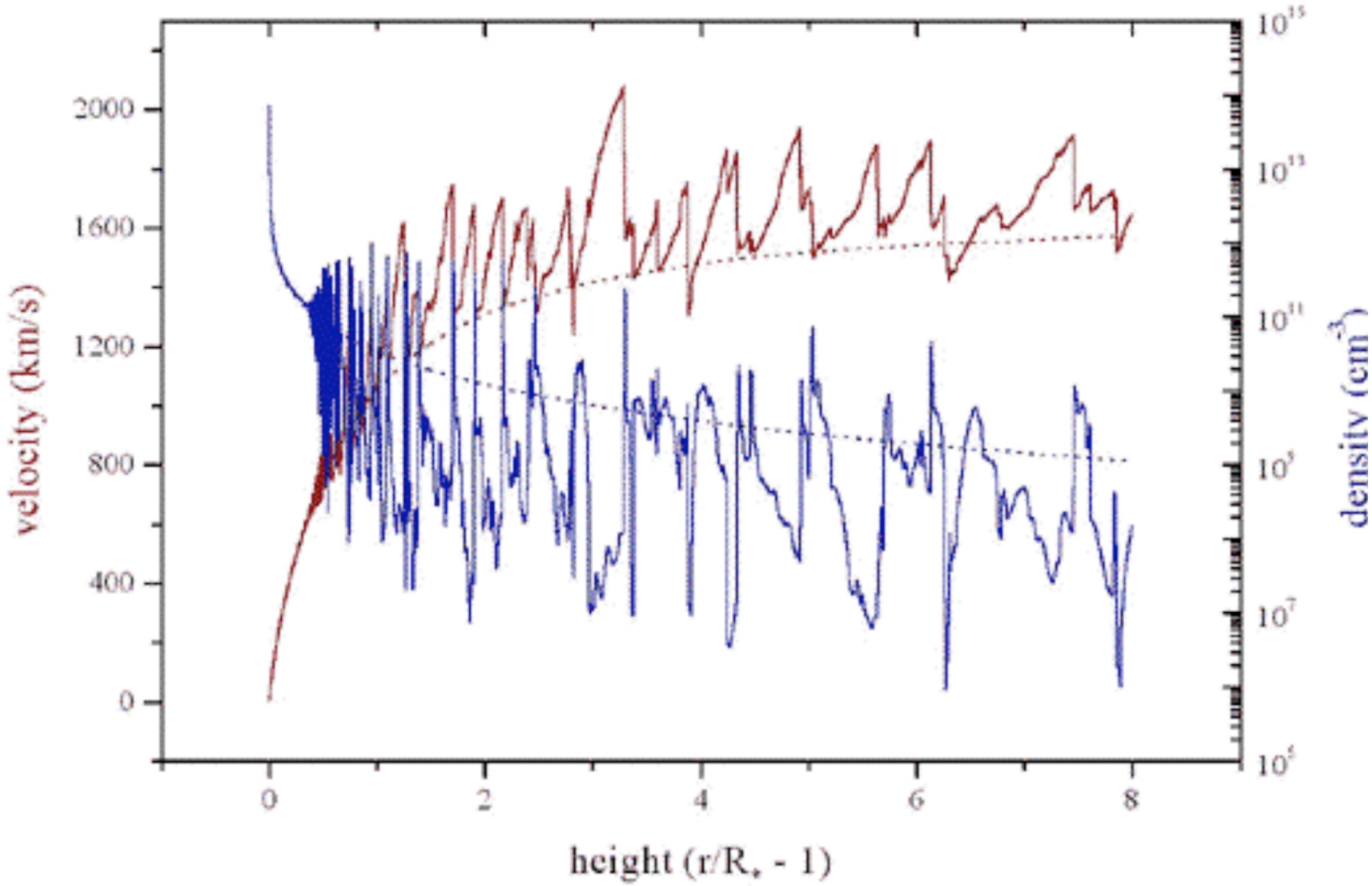


Time dependent models of the winds show lots of structure: turbulence, shock waves, collisions between "clouds"

This chaotic behavior is predicted to **produce X-rays** through **shock-heating** of some small fraction of the wind.



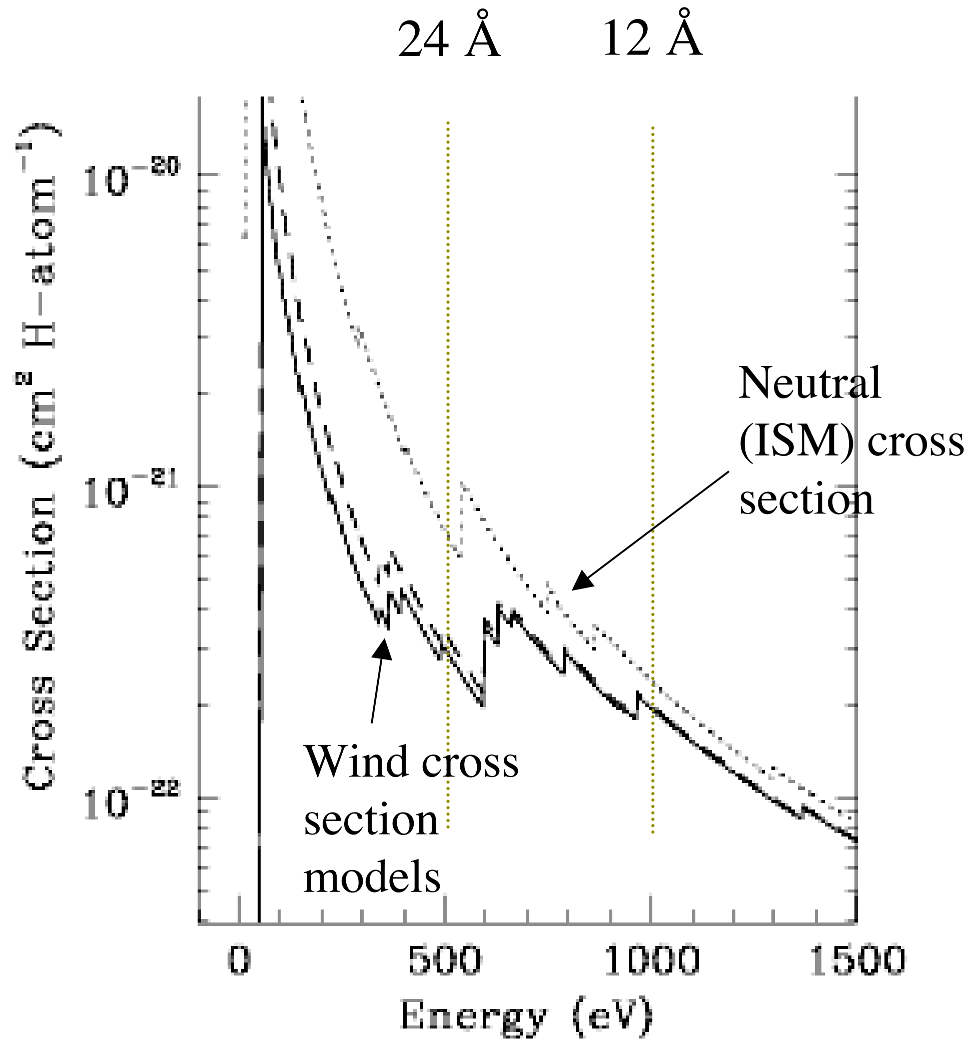
A snapshot at a single time from the same simulation. Note the discontinuities in velocity. These are shock fronts, compressing and **heating** the wind, producing **X-rays**.



Even in these instability shock models, most of the wind is cold and is a source of X-ray continuum opacity

The massive winds of O stars are expected to be **optically thick** to soft X-rays…the inner tens of R_* may be heavily absorbed: or so it was thought.

The **wavelength dependence** of individual lines leads to the expectation that different absorption characteristics will be seen in different lines from a given star.

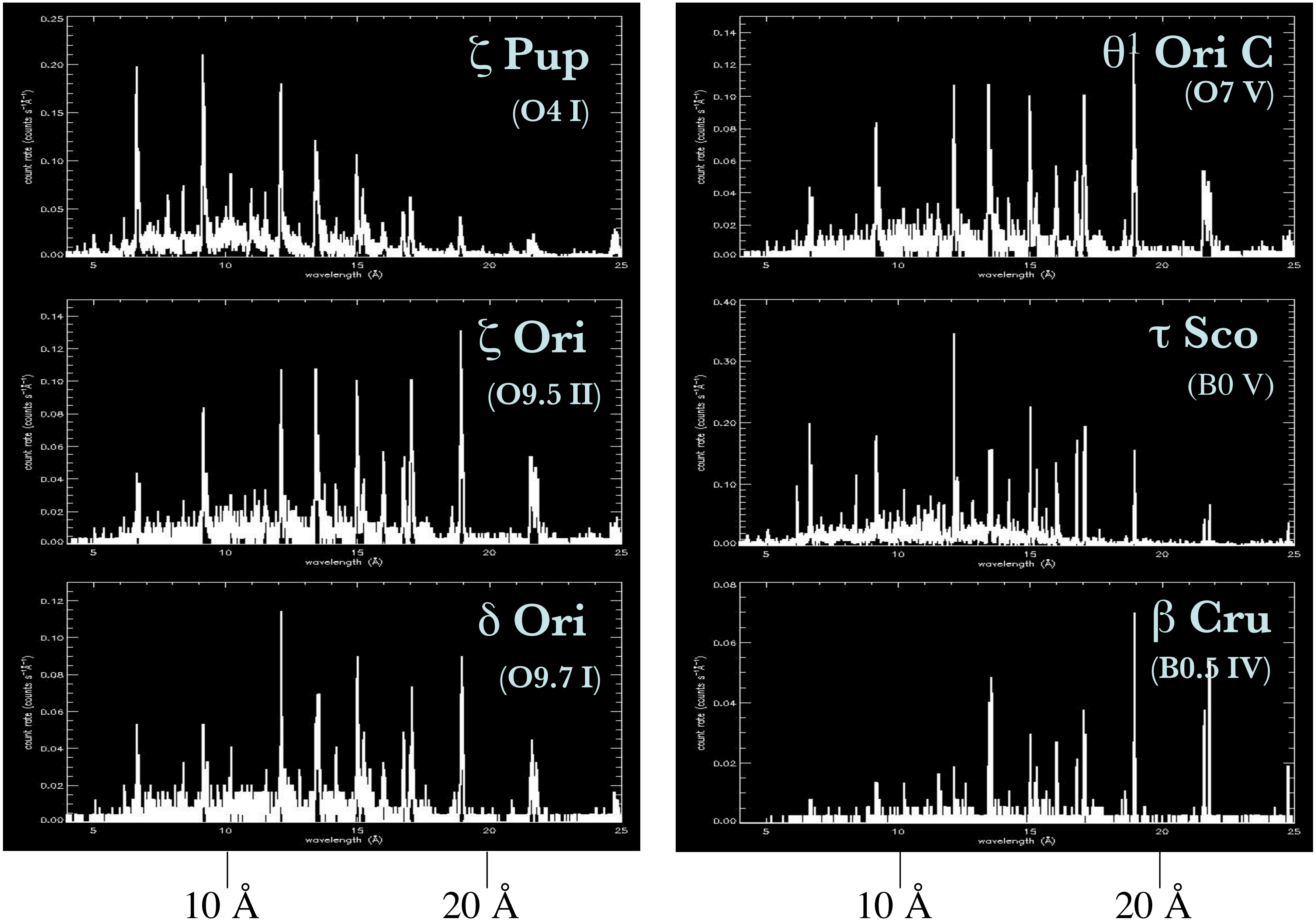


The *Chandra* Archive of Hot Stars

Because of the pathetically small effective area of the gratings, only a handful of single OB stars can produce high-quality spectra – maybe a dozen total; we will look at several representative single OB stars

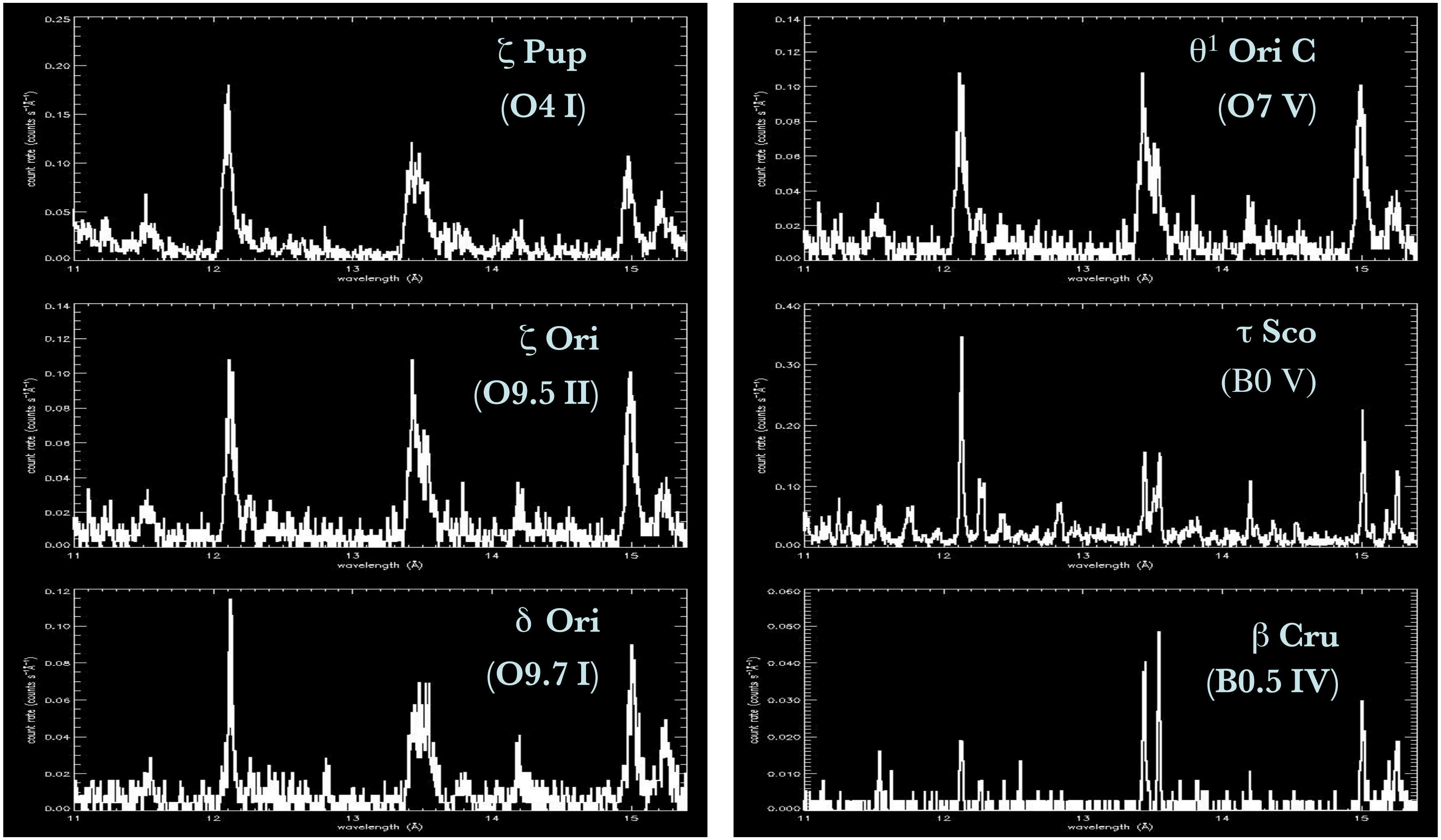
Star	**Sp. Ty.**	**M_{dot}**	**V_{inf}**	**comments**
ζ Pup	O4	2.5 (-6)	2500	
ζ Ori	O9.5 II	1(-6)	1860	
δ Ori	O9.7 I	1(-6)	2000	
θ^1 Ori C	O7 V	4(-7)	2500	1100 G dipole magnetic field
τ Sco	B0 V	3(-8)	1500	Unusually X-ray bright and hard
γ Cas	B0.5 Ve	5(-8)	1800	Same, but more so
β Cru	B0.5 IV	~5(-9)	1200	Beta Cep var.

Global appearance of spectra (*Chandra* MEG)



Focus in on a characteristic portion of the spectrum

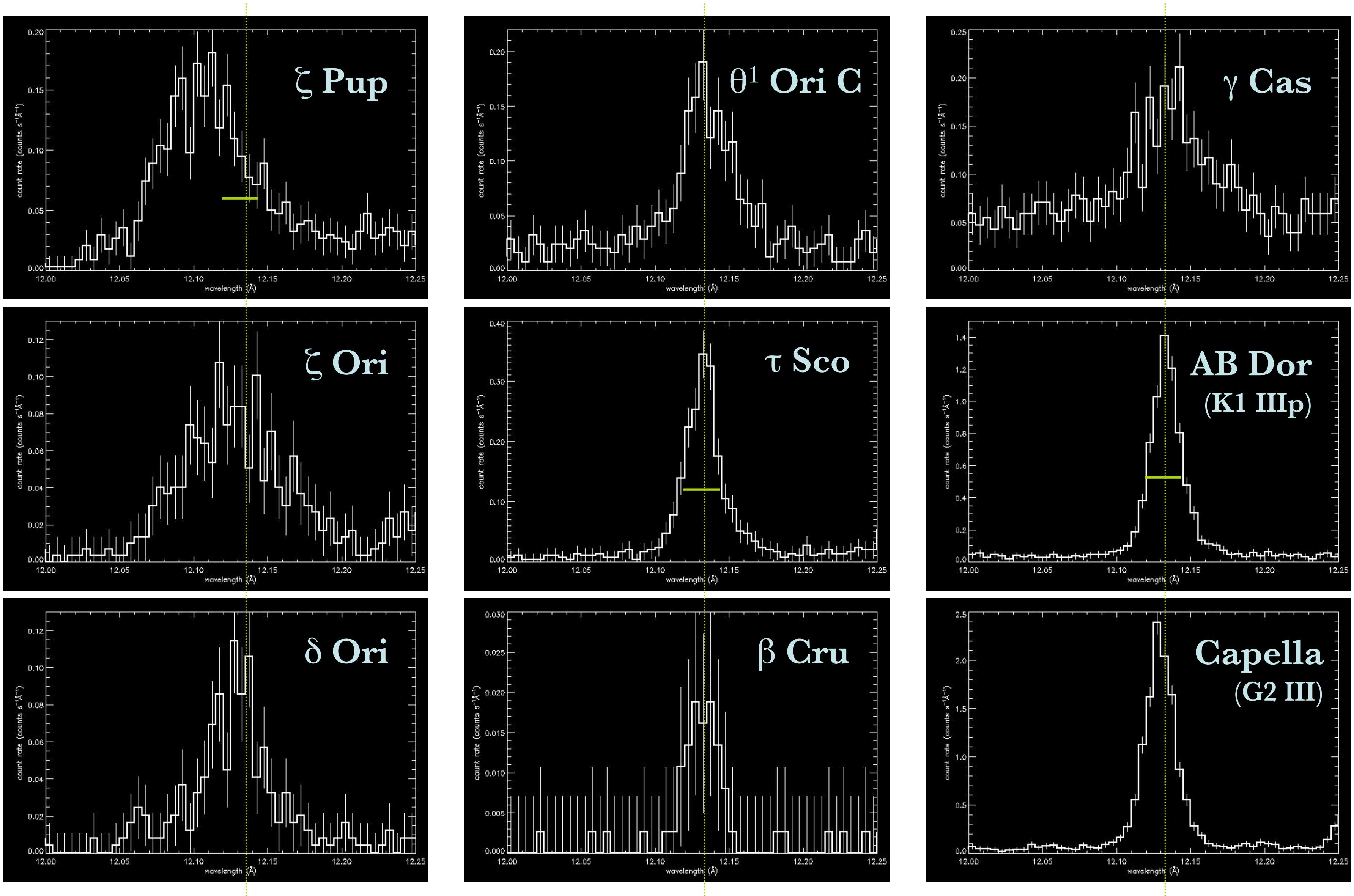
12Å 15Å 12Å 15Å



Ne X Ne IX Fe XVII Ne X Ne IX Fe XVII

There is clearly a range of line profile morphologies from star to star

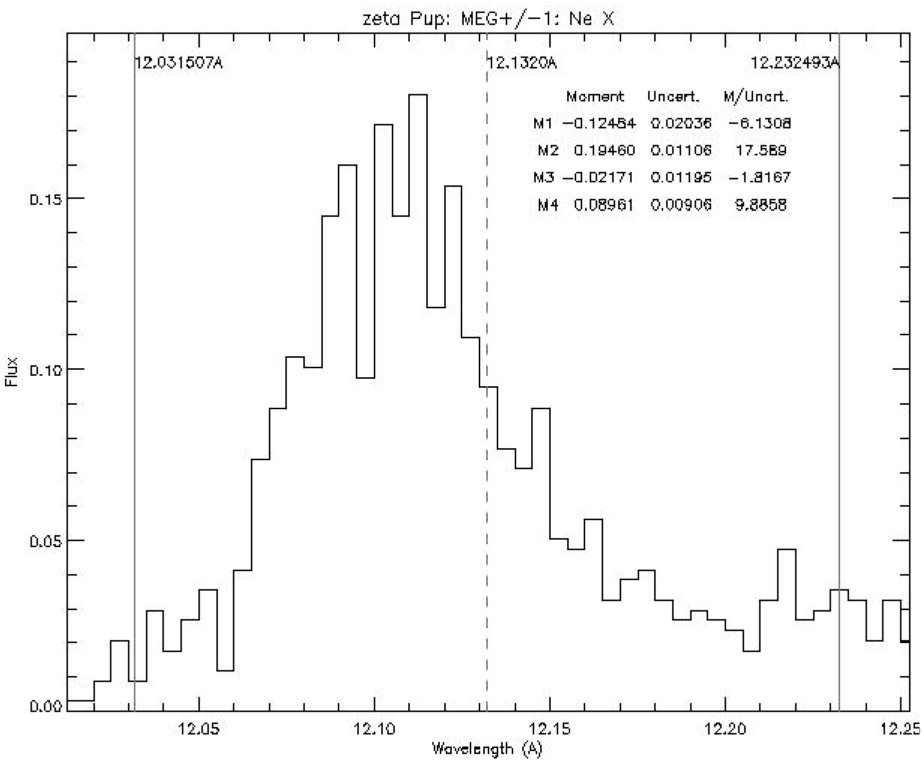
Differences in the line shapes become apparent when we look at a single line (here Ne X, Lyα)

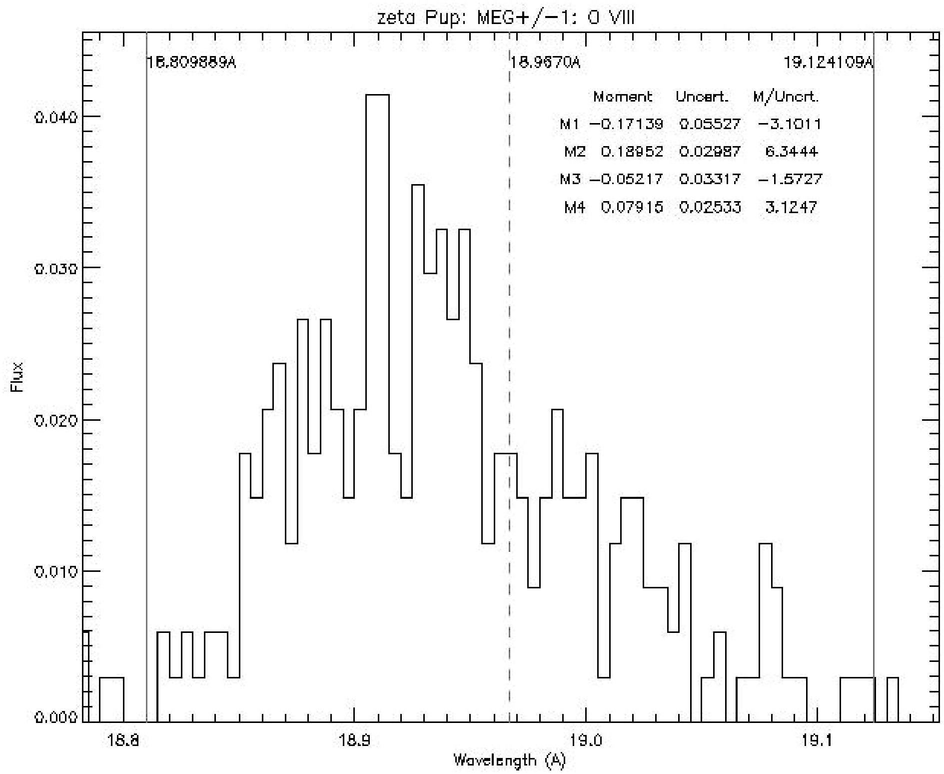


Now let's focus on individual lines

ζPup: prototypical O supergiant wind

We can look at the line profiles **non-parametrically**: are they blueshifted? asymmetric?

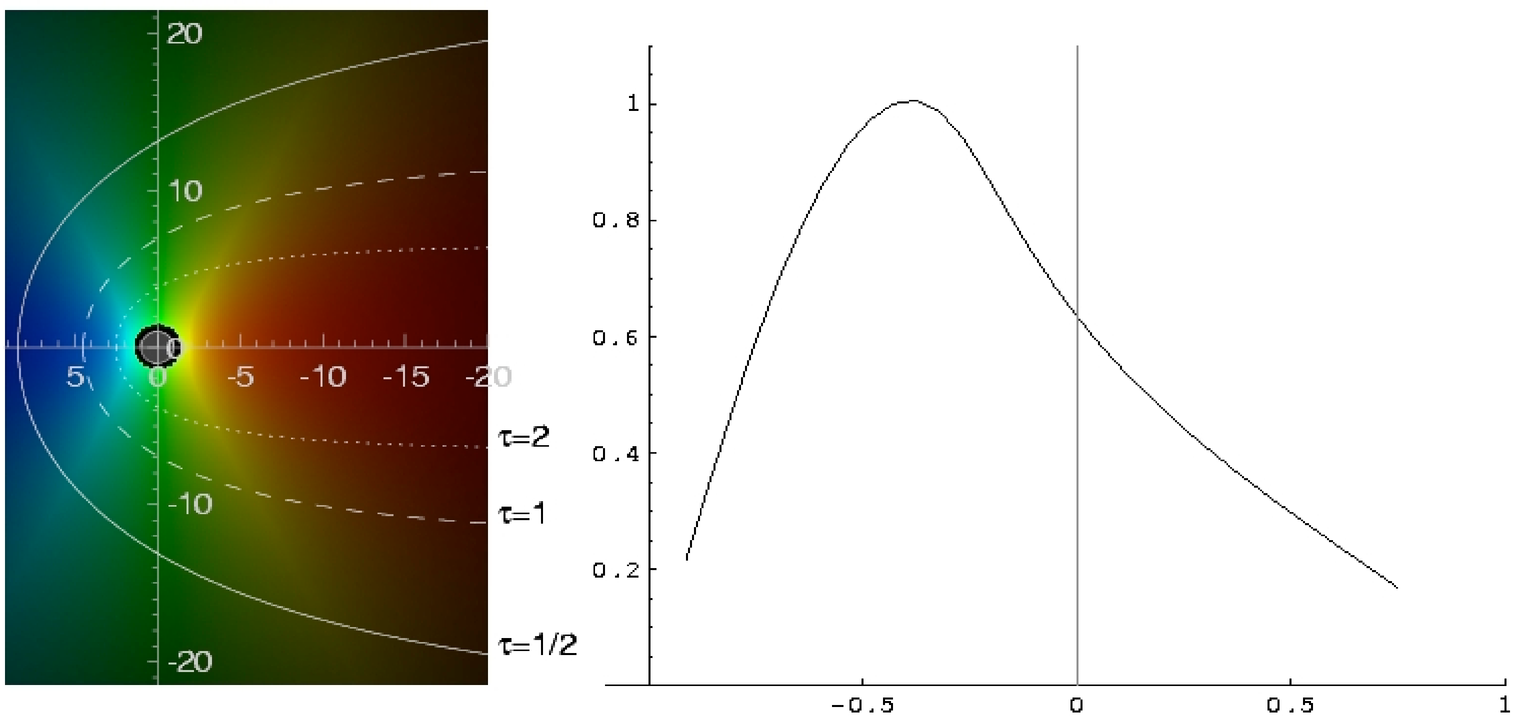




We calculate the first four *moments* of each line profile: the first moment is proportional to the wavelength shift while the third moment, the skewness, is an indicator of asymmetry.

Our idea: fit lines with the *simplest* model that can do the job, and use one that, while based in physics, is *general* in the sense that any number of physical models can be tested or constrained based on the model fits.

From Owocki & Cohen (2001): spherically symmetric, two-fluid (hot plasma is interspersed in the cold, x-ray absorbing bulk wind); beta velocity law.



Visualizations of the wind use *hue* to indicate *line-of-sight velocity* and *saturation* to indicate *emissivity*; corresponding profiles are plotted vs. scaled velocity where x = -1,1 correspond to the terminal velocity.

The model has four parameters:

$$\beta : v(r) = (1 - R_* / r)^{\beta}$$

$$R_o, q : j \propto \rho^2 r^{-q} \quad \text{for } r > R_o$$

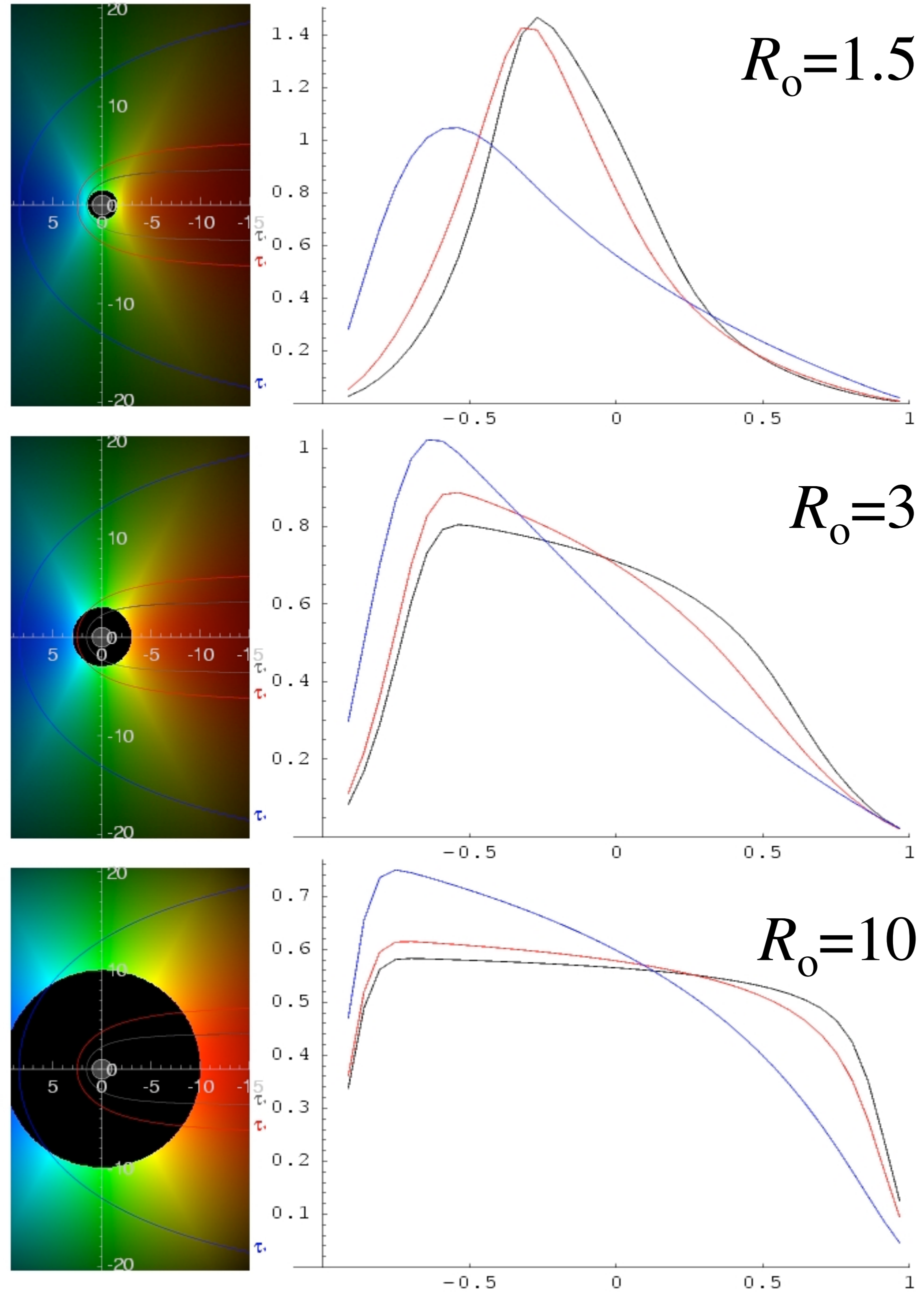
$$\tau_* : \tau(p = 0; z) = \tau_* \int_z^{\infty} \frac{dz'}{r'^2 (1 - \frac{1}{r'})^{\beta}}$$

where $$\tau_* \equiv \frac{\kappa \dot{M}}{4 \pi R_* v_{\infty}}$$

The line profile is calculated from:

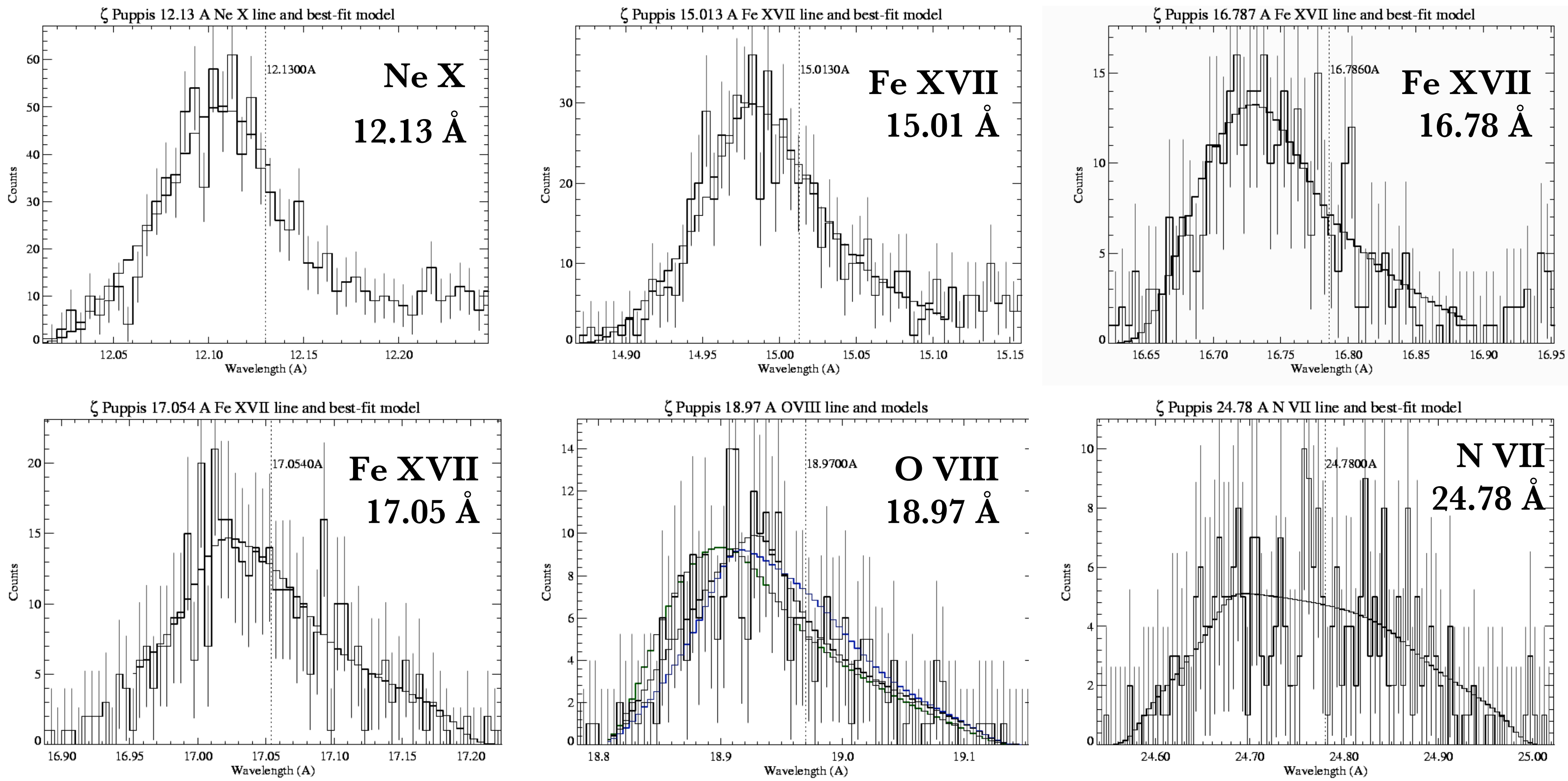
$$L_{\lambda} = 8 \pi^2 \int_{-1}^{1} \int_{R_*}^{\infty} j e^{-\tau} r^2 dr d\mu$$

Increasing R_o makes lines broader; increasing τ_* makes them more blueshifted and skewed.

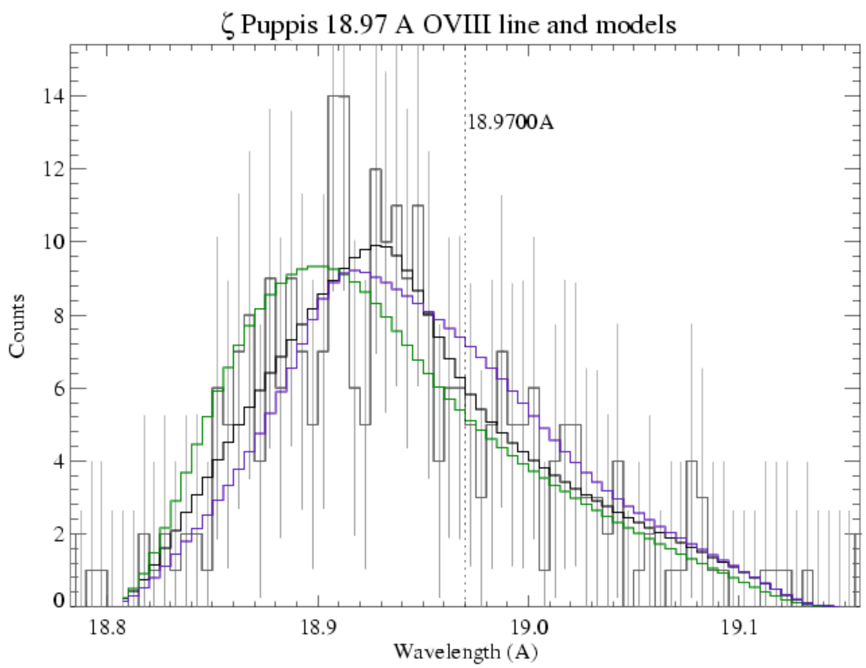


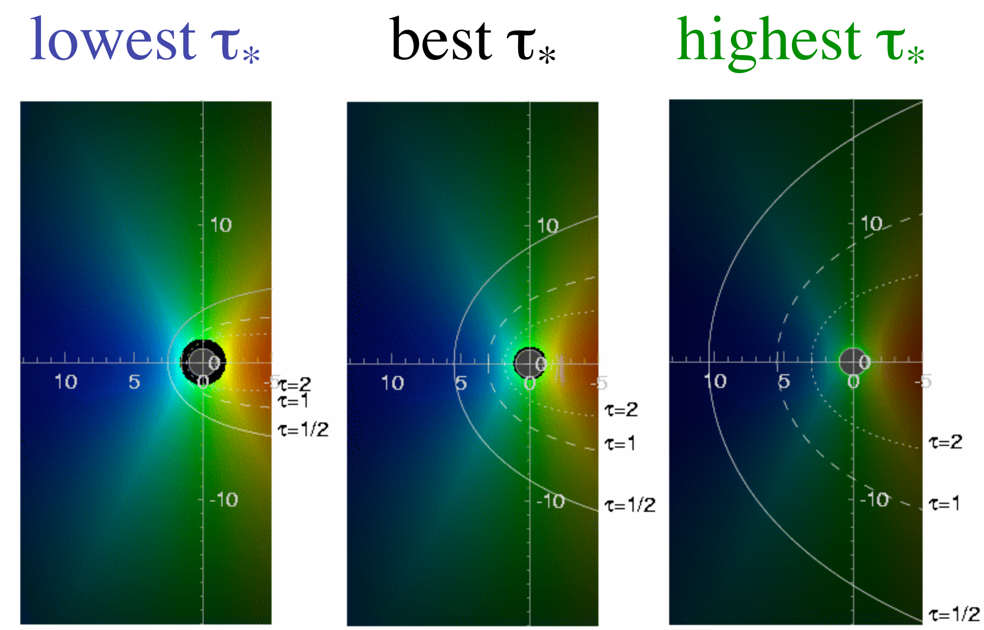
τ_*=1,2,4

We fit all the (8) unblended strong lines in the *Chandra* spectrum of ζ Pup: all the fits are statistically good



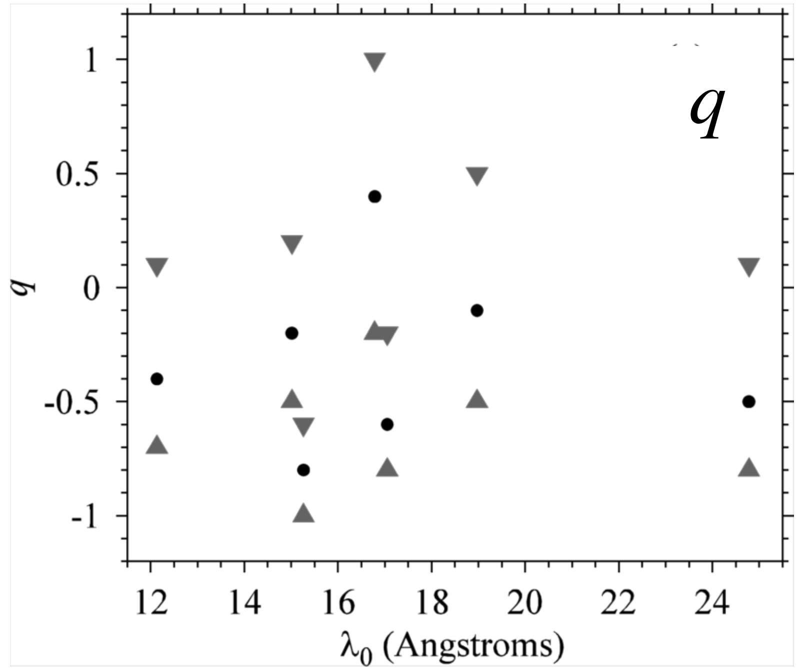
We place *uncertainties* on the derived model parameters

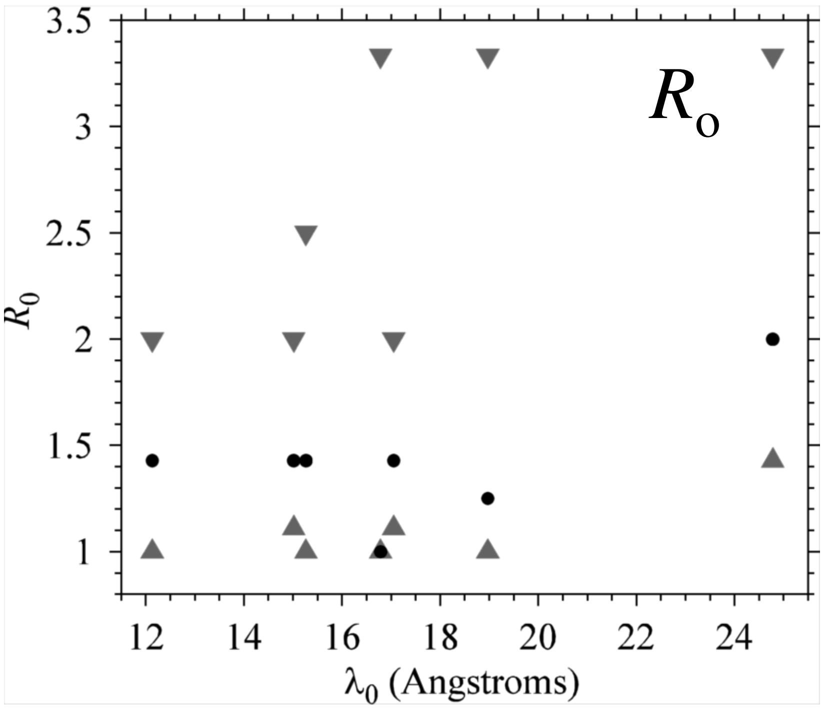


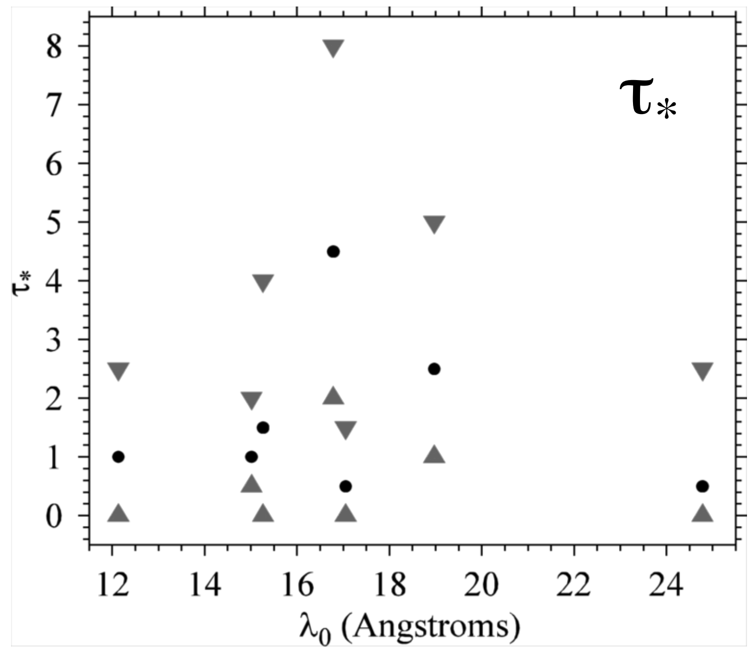


Here we show the best-fit model to the O VIII line and two models that are marginally (at the 95% limit) consistent with the data; they are the models with the highest and lowest τ_* values possible.

Graphical depiction of the best fit (black circles) and 95% confidence limits (gray triangles) on the three fitted parameters for seven of the lines in the ζ Pup spectrum.







Lines are well fit by our four parameter model (β is actually held constant at β=1; so three free parameters): ζ Pup's X-ray lines are consistent with a spatially distributed, spherically symmetric, radially accelerating wind scenario, with reasonable parameters:

τ_{*}~1 :4 to 15 times less than predicted

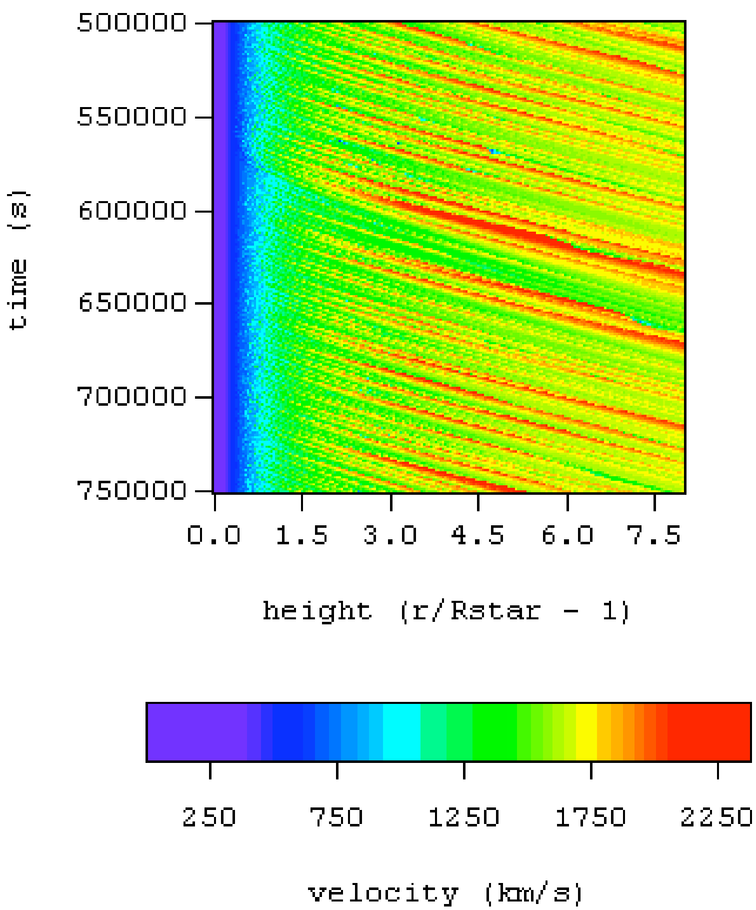
R_{o}~1.5

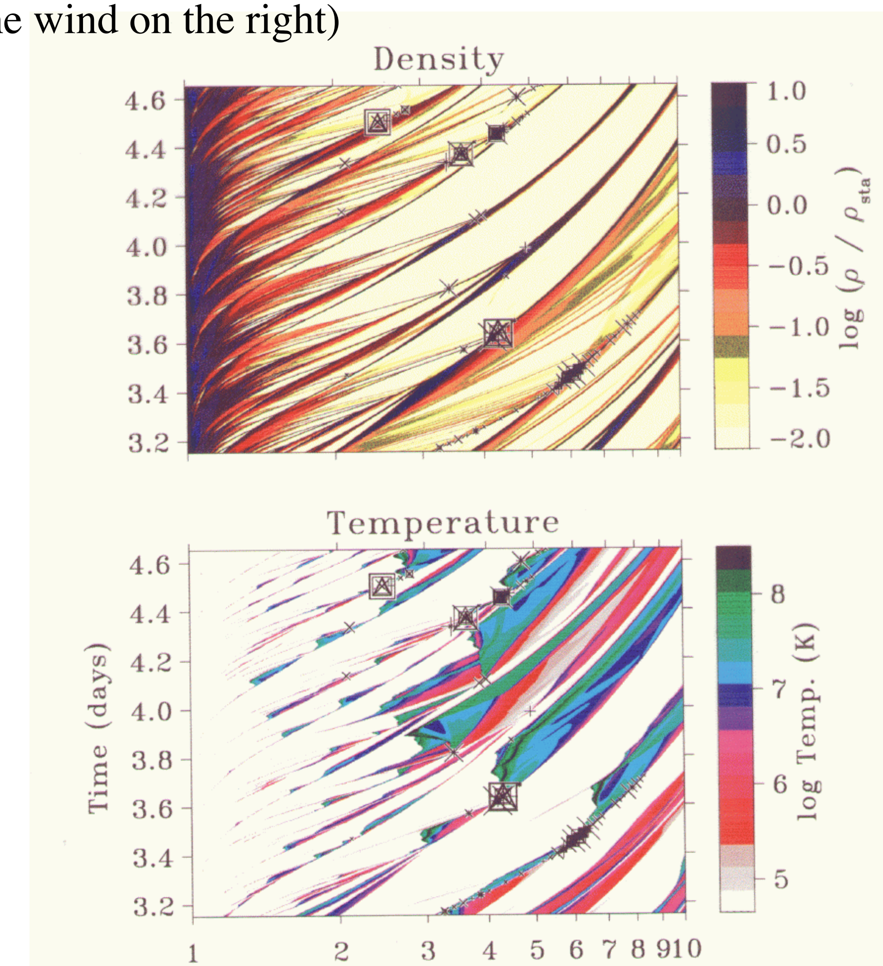
q~0

But, the level of *wind absorption is significantly below* what's expected.

And, there's *no significant wavelength dependence* of the optical depth (or any parameters).

R_o of several tenths of a stellar radius is expected based on numerical simulations of the line-force instability (self-excited on the left; sound wave purturbations at the base of the wind on the right)



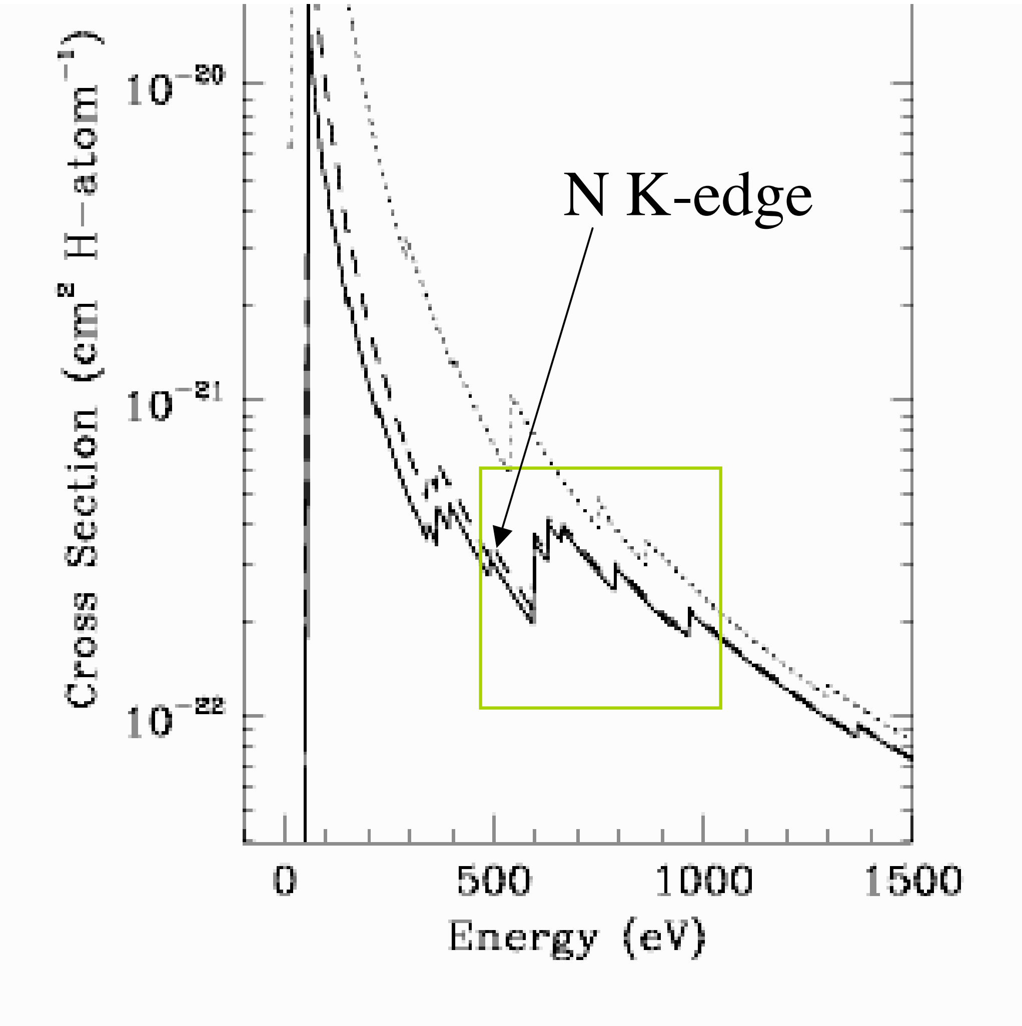


Location of the X-ray-emitting plasma near the photosphere is indicated by He-like *f/i* ratios (Kahn et al. 2001)

We do expect some wavelength dependence of the cross sections (and thus of the wind optical depth), BUT the lines we fit cover only a modest range of wavelengths. And in the case of ζ Pup, nitrogen overabundance (not in calculation shown at right) could flatten out the wavelength dependence even more.

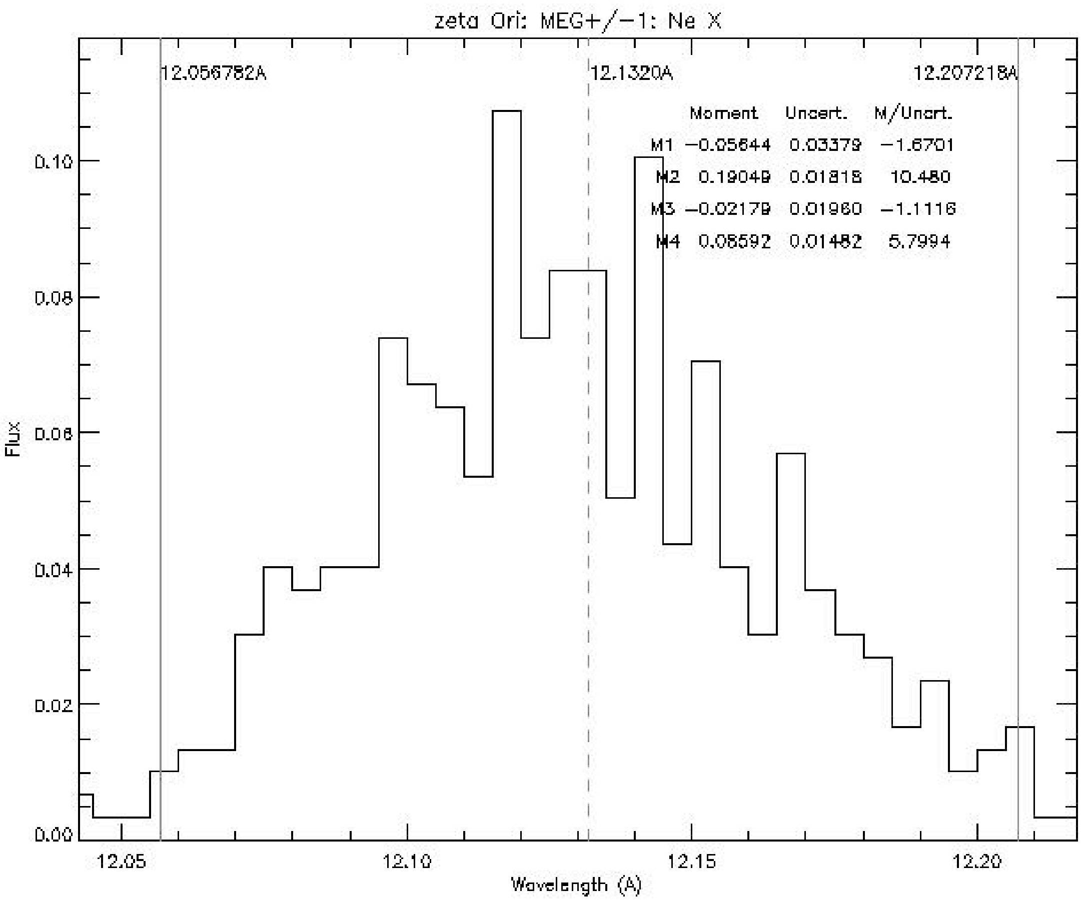
OR perhaps **clumping** plays a role. And clumping (alt. "porosity") certainly could play a role in the overall reduction of wind optical depth.

Wind opacity for canonical B star abundances.

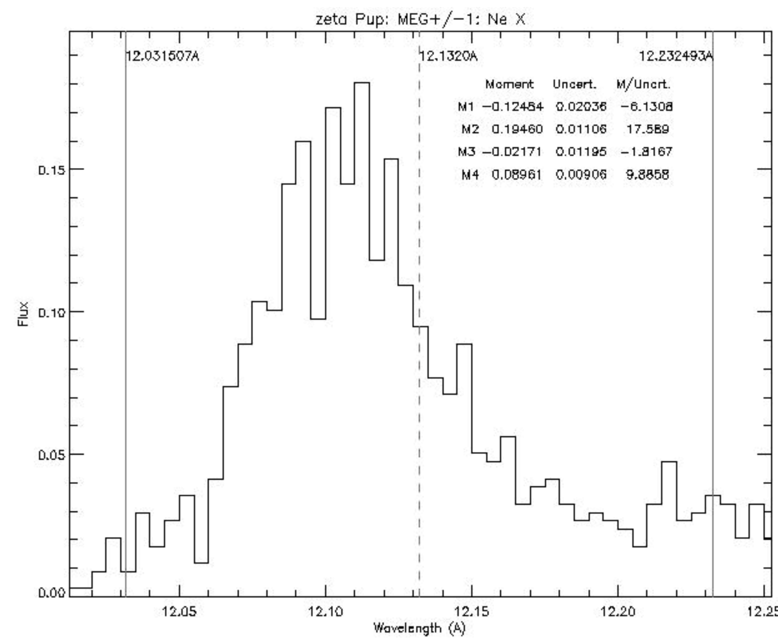


Note: dotted line is interstellar.

Do the other O supergiants, ζ Ori and δ Ori, fit into the wind-shock paradigm?

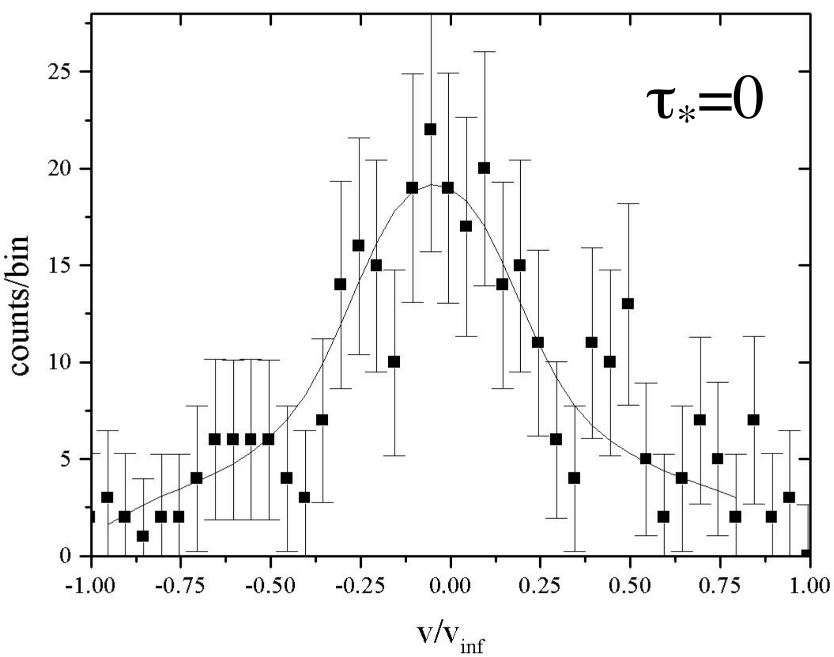


The Ne X line in ζ Ori (left) is skewed and blueshifted (>1σ), though not as much as the same line in ζ Pup (below)

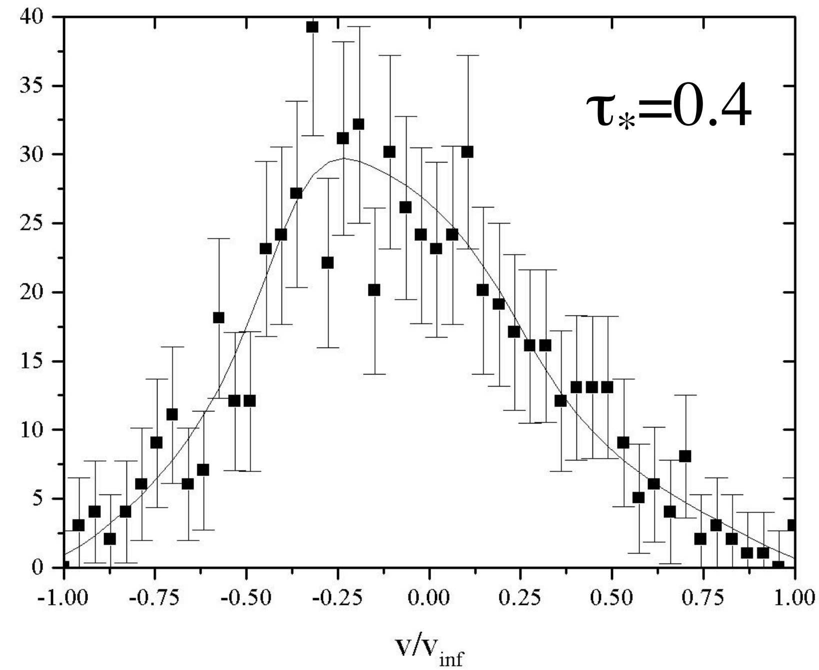


The strong lines in these other O supergiants can also be fit by the simple spherically symmetric wind model

δ Ori Fe XVII 15.01 Å



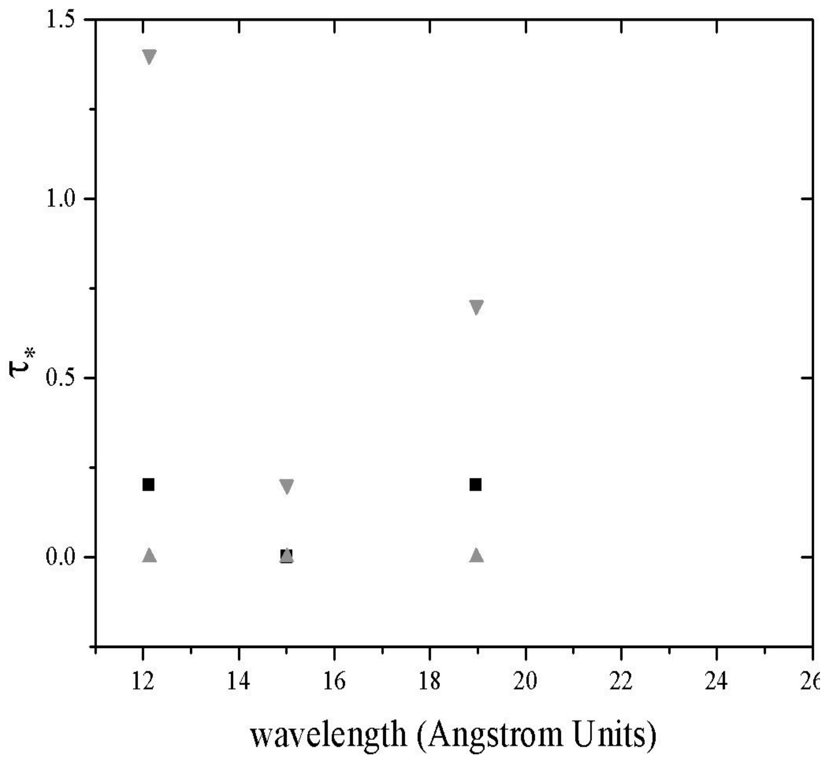
ζ Ori O VIII 18.97 Å



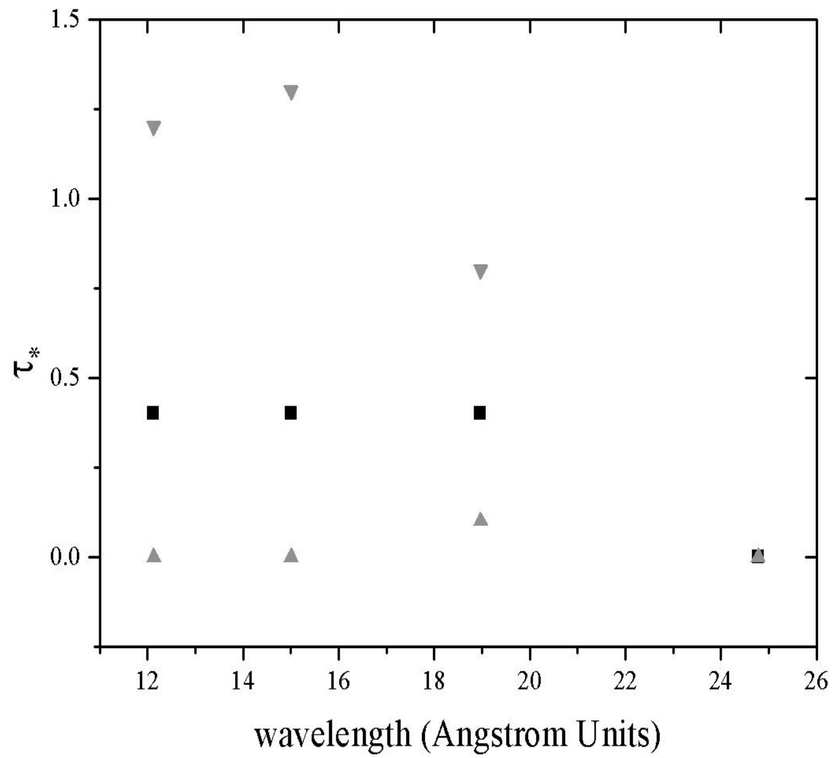
Though they are clearly less asymmetric and a little narrower

Best-fit τ_* values are a few tenths, although a value of zero can be ruled out at the 95% confidence limit in all but one line…however, values above 0.5 or even 1 cannot be ruled out in most cases

δ Ori

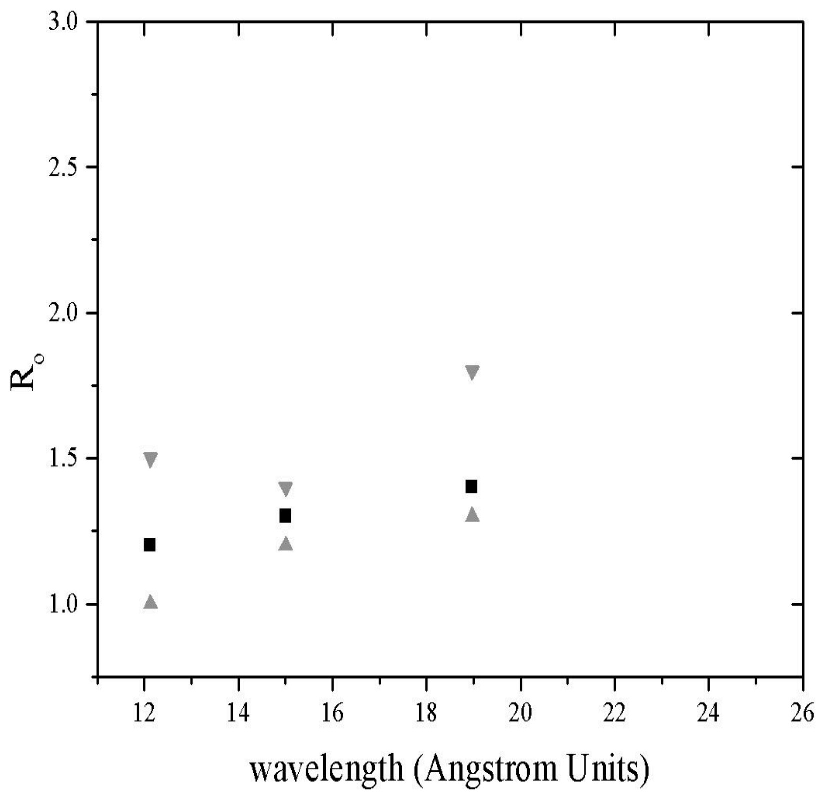


ζ Ori

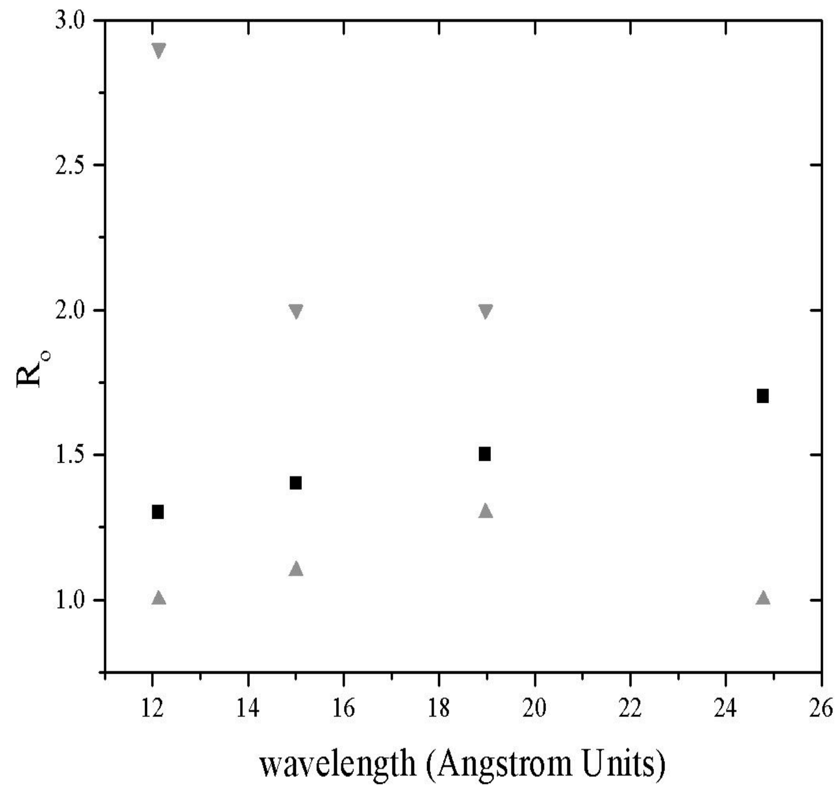


R_o, the radius of the onset of X-ray emission is within the first stellar radius above the photosphere; and consistent with a height of 3/10 R_* or less at the 95% confidence level for all the lines

δ Ori



ζ Ori



It's these **small R_o values** that produce the relative **narrowness** of the lines (compared to ζ Pup).

Conclusions for normal, O supergiants

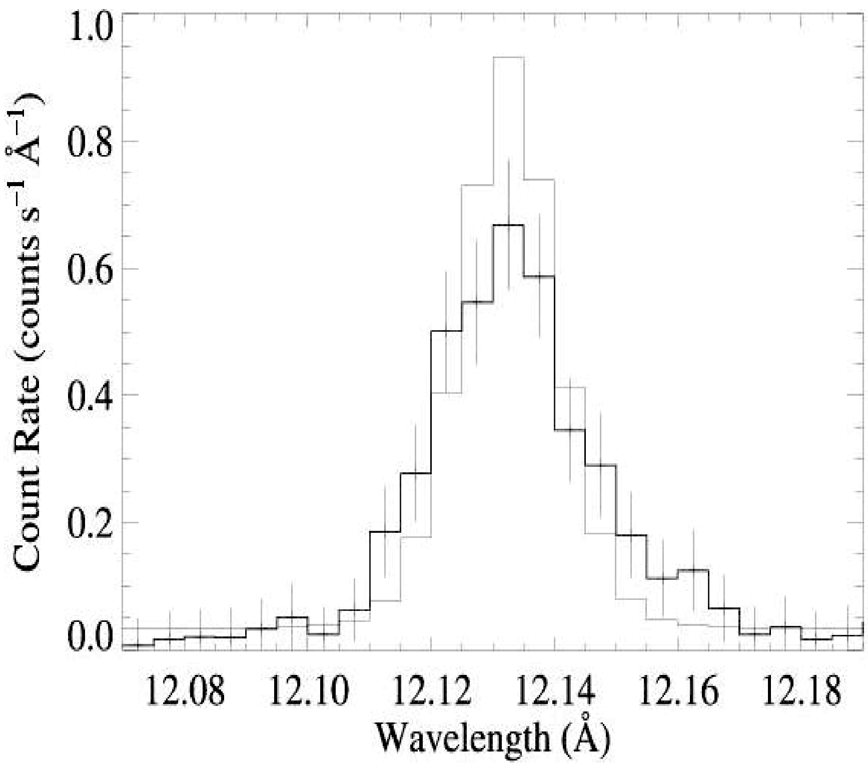
Spherically symmetric, standard wind-shock model fits the data

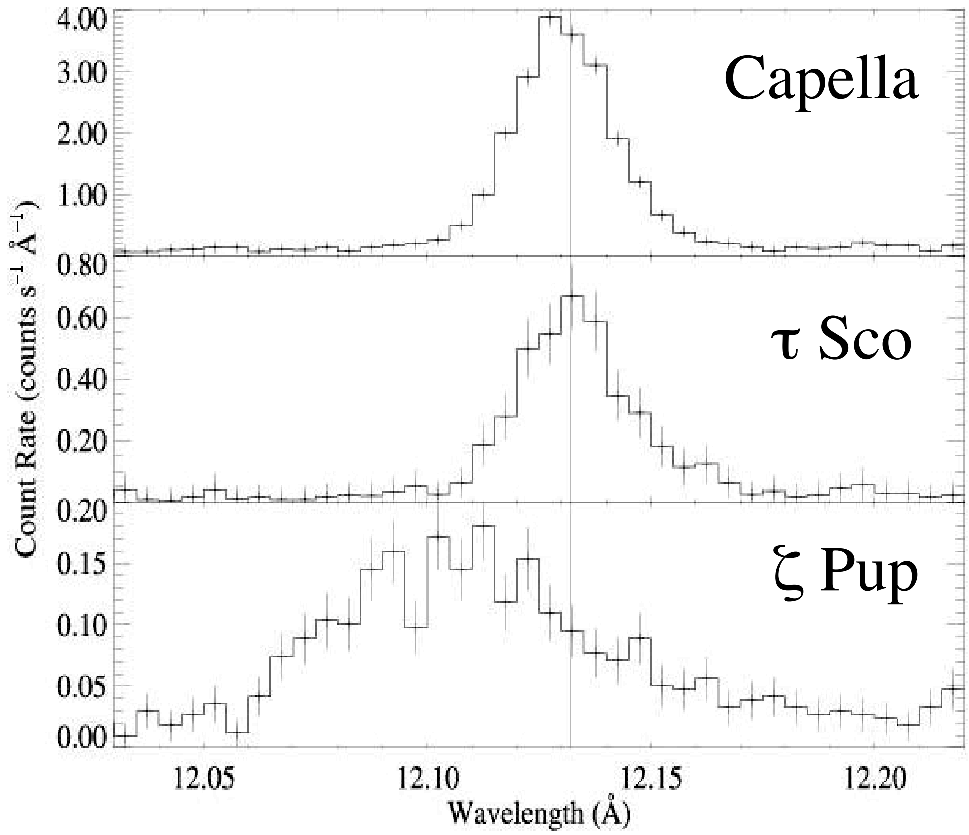
But the level of continuum absorption in the wind must be reduced from expected values by factors of ~5 (clumping?)

Other diagnostics (DEM, abundances, density-sensitive line ratios) provide information too; generally consistent with the standard picture.

What about the stars with the harder X-rays and narrower lines: θ^1 Ori C and τ Sco?

τ Sco's Ne X line overplotted with a delta function model.

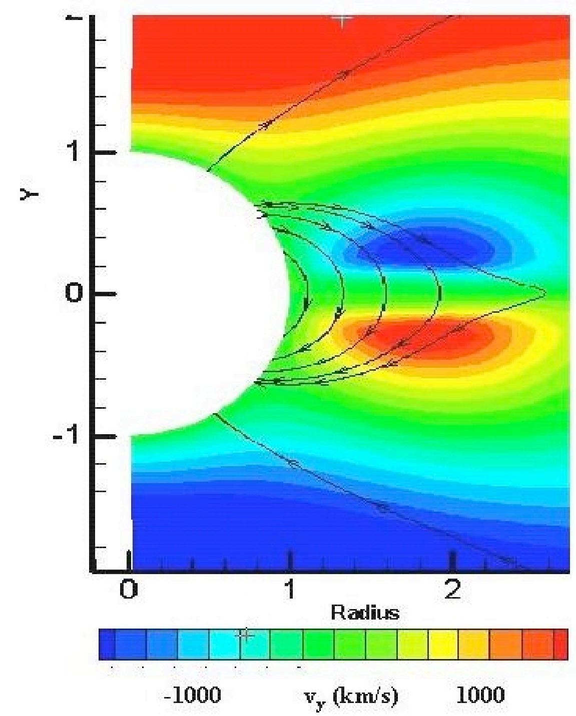




The lines in τ Sco look more like those in coronal sources…and the lines in θ^1 Ori C aren't a whole lot broader.

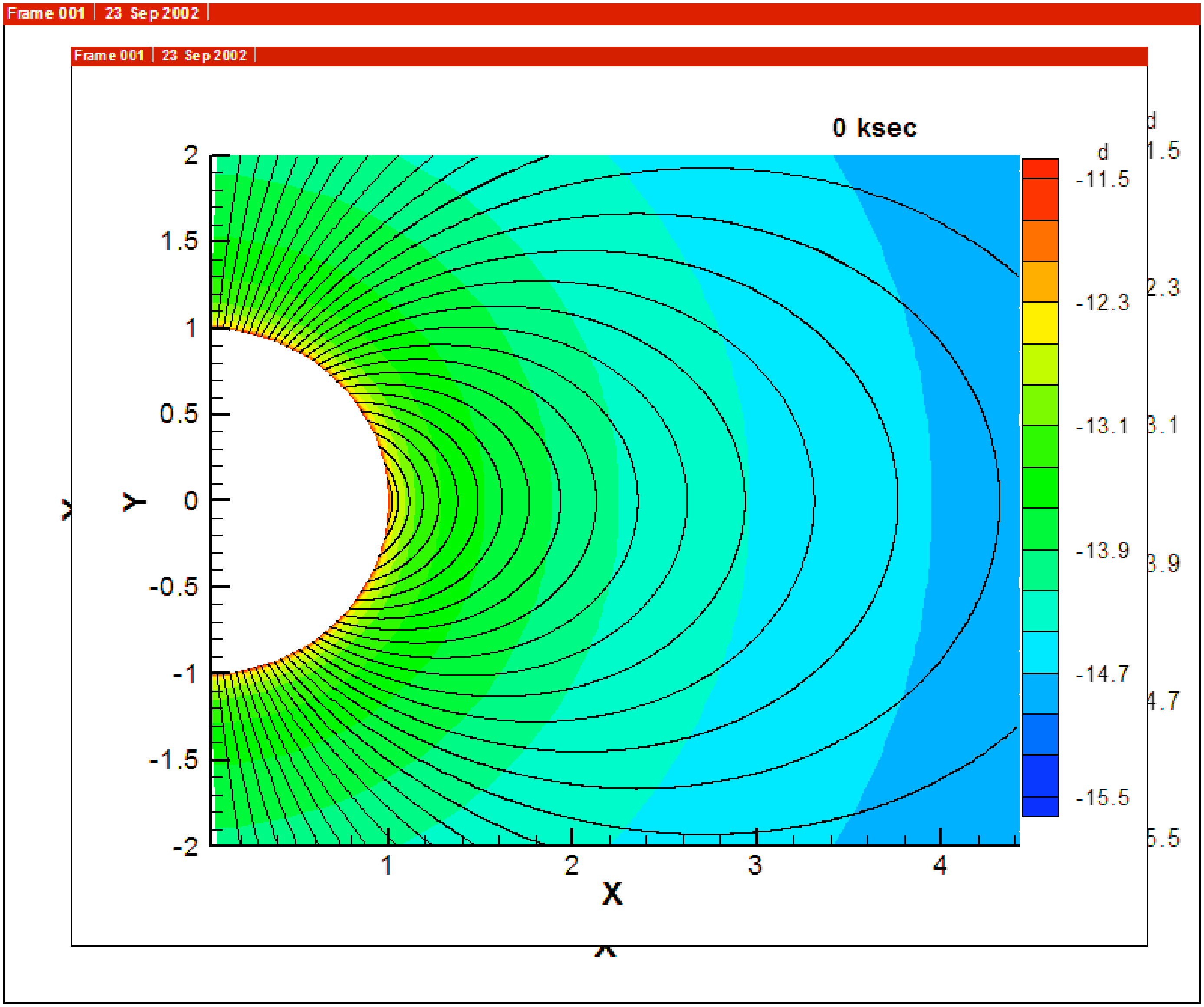
But the large x-ray luminosities and hard x-ray spectra already argue against instability-generated shocks…
…and suggest that a **hybrid wind-magnetic** model might be appropriate, especially on θ^1 Ori C, on which an *1100 G dipole field has been discovered*

ud-Doula and Owocki (2001) have performed MHD simulations of magnetically channelled winds: Equatorward flow inside closed field lines and associated strong shocks are seen.

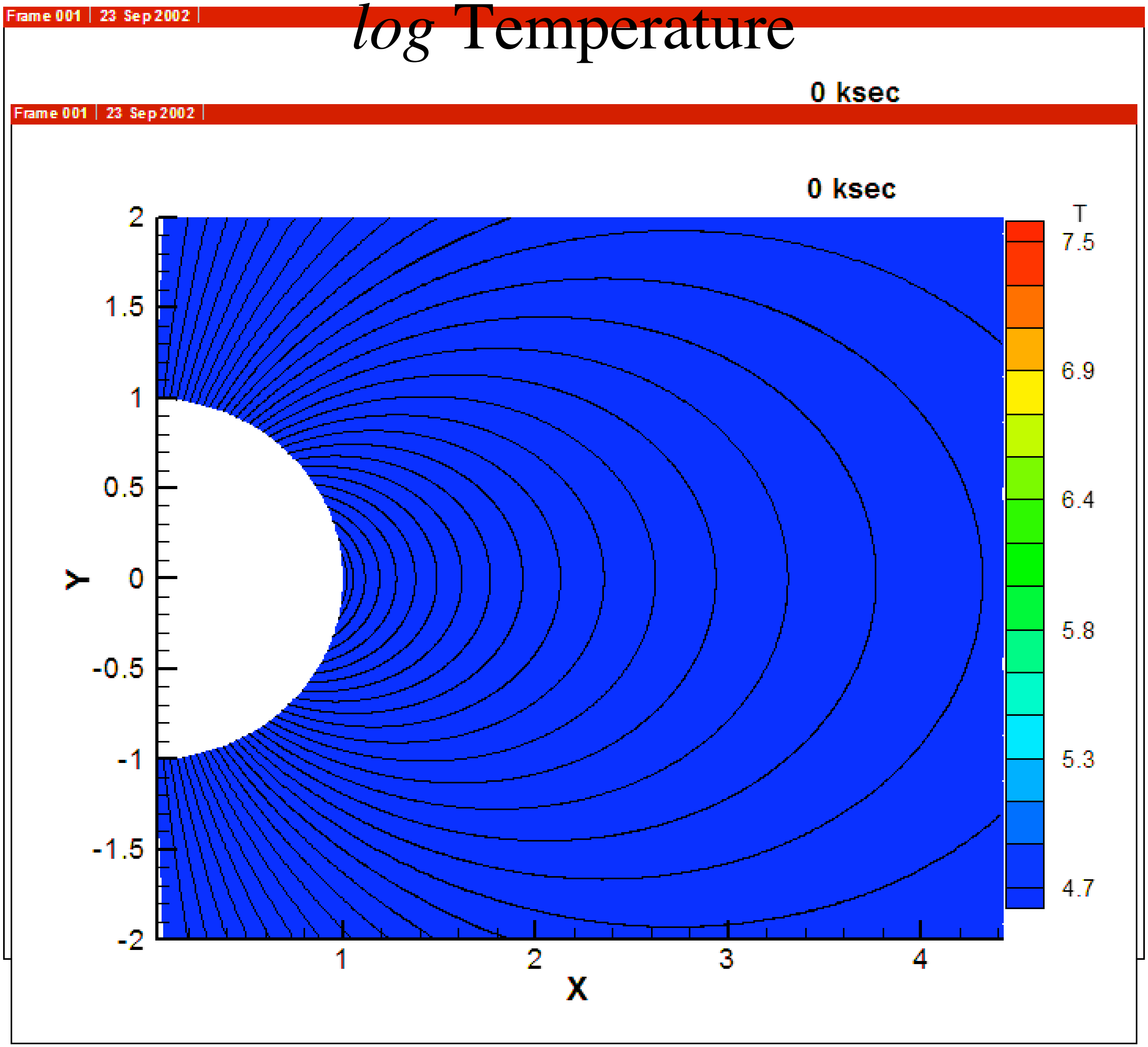


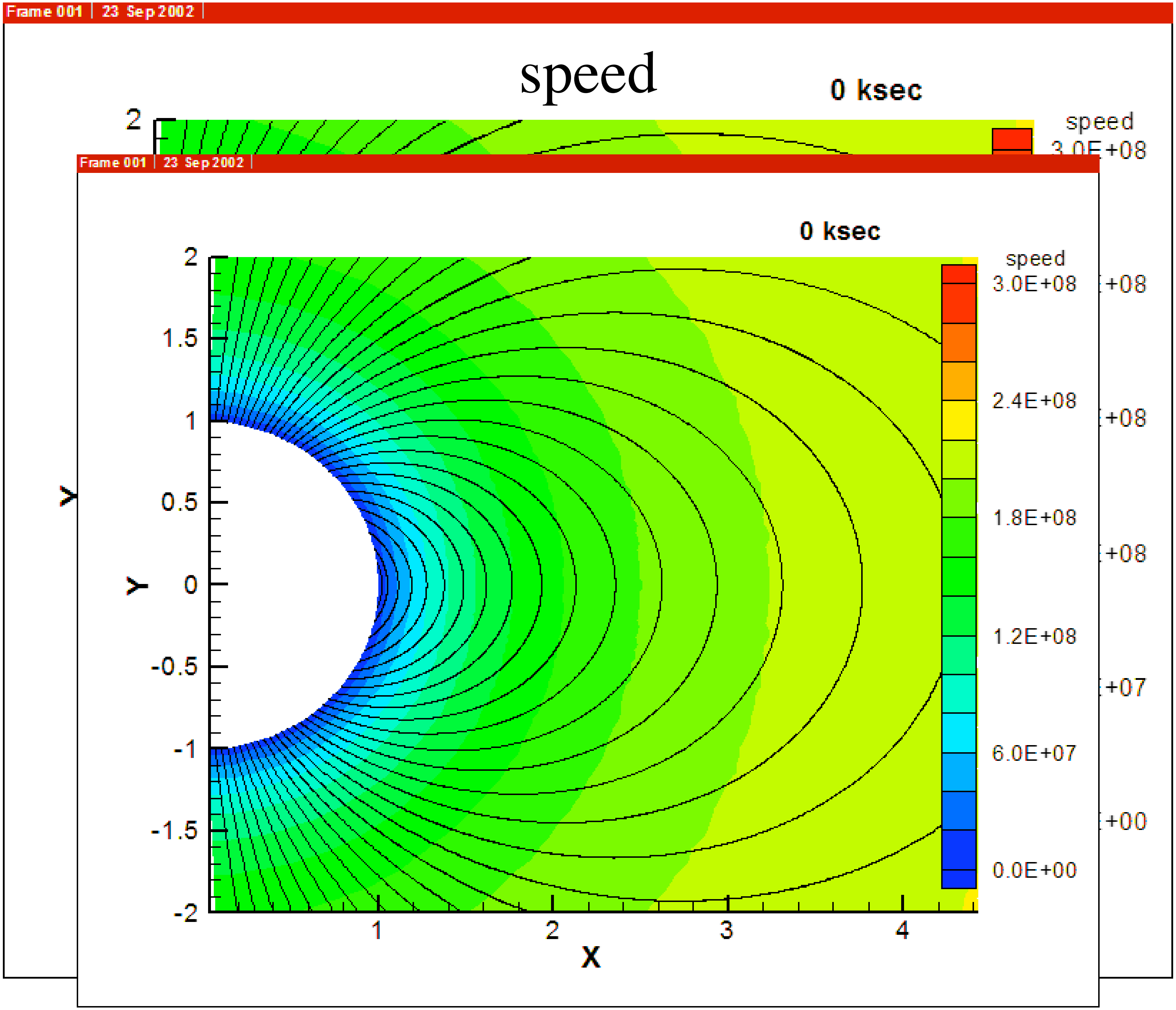
y-component
of velocity

ud-Doula has made models specific to θ^1 Ori C, and included radiative cooling for the first time: This is a movie of density, evolving from an initial spherically symmetric steady-state wind.



log Temperature




Frame 001 | 23 Sep 2002
speed
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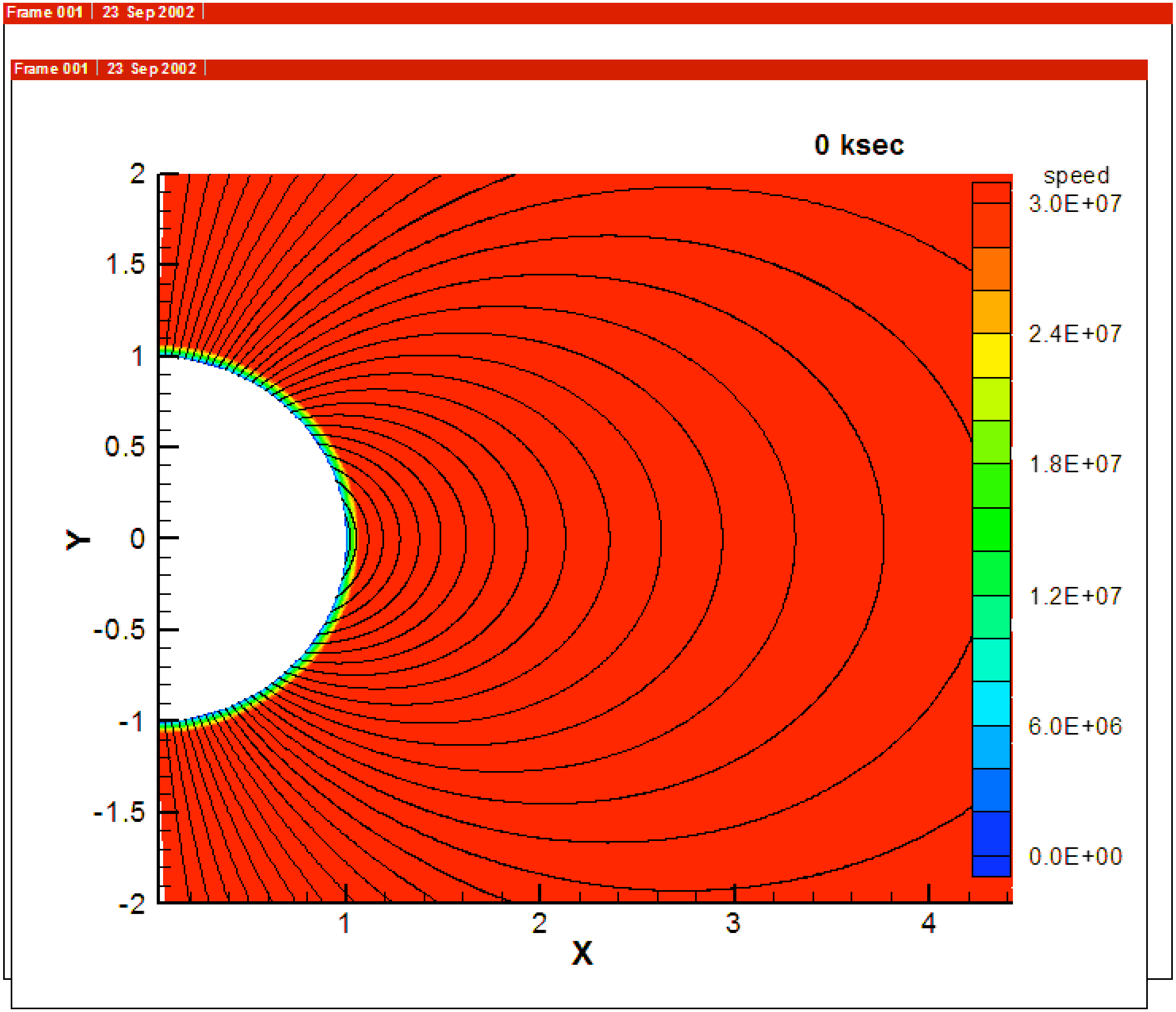
1.2E+08
6.0E+07
0.0E+00
Y
X
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
1
2
3
4

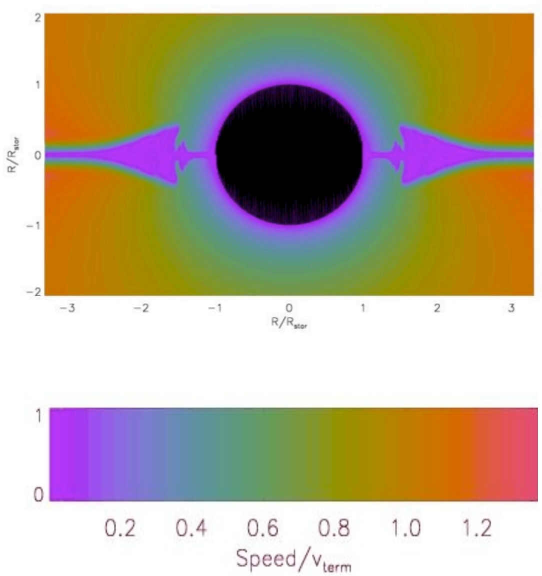
Speed (again), but with low speeds emphasized



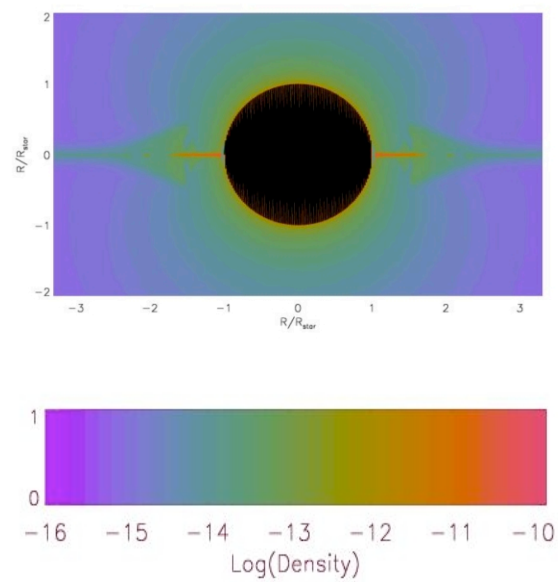
We looked at some snapshots from these simulations and synthesized line profiles (and emission measure distributions and light curves)

This first snapshot of θ^1 Ori C is from a time when the hot plasma is relatively placid, filling the closed loop region

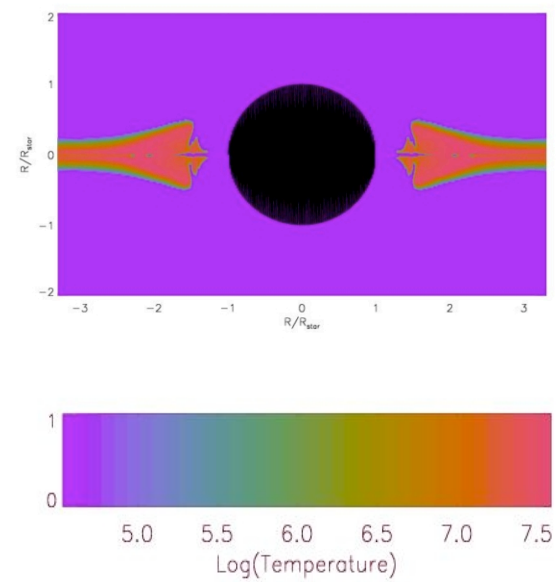
speed



density



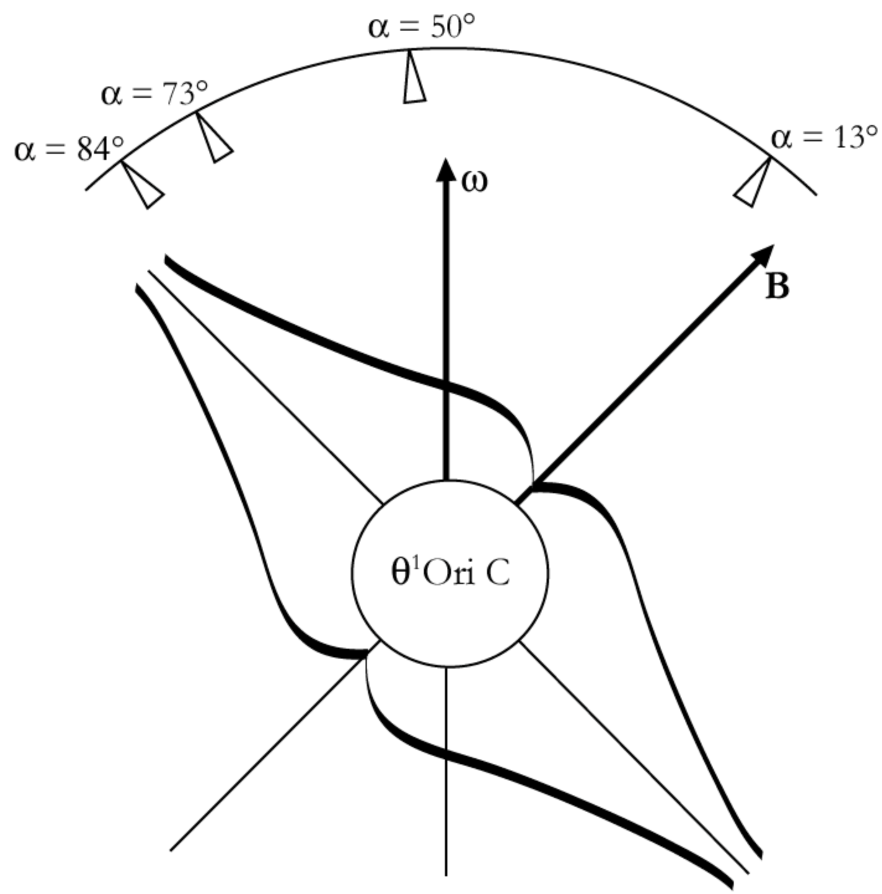
temperature



Note: throughout, the speed is in terms of an assumed terminal speed of 2500 km s^{-1}

The geometry and viewing angle are relatively well established for this star.

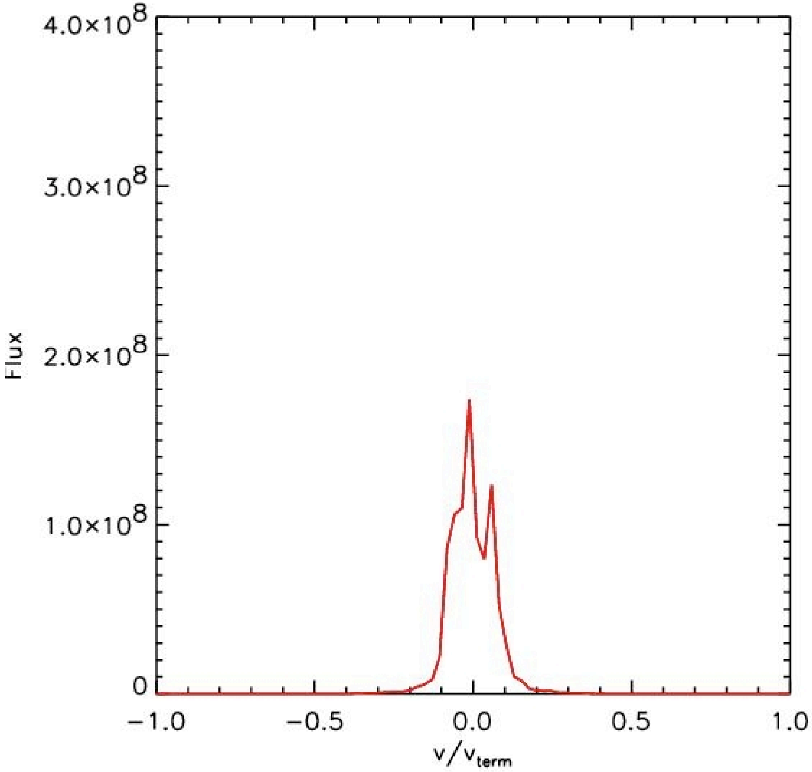
There is a 45°tilt between the rotation axis and both the magnetic axis and the direction of the Earth: we see a full range of viewing angles of the magnetosphere, and have *Chandra* observations for four of them.

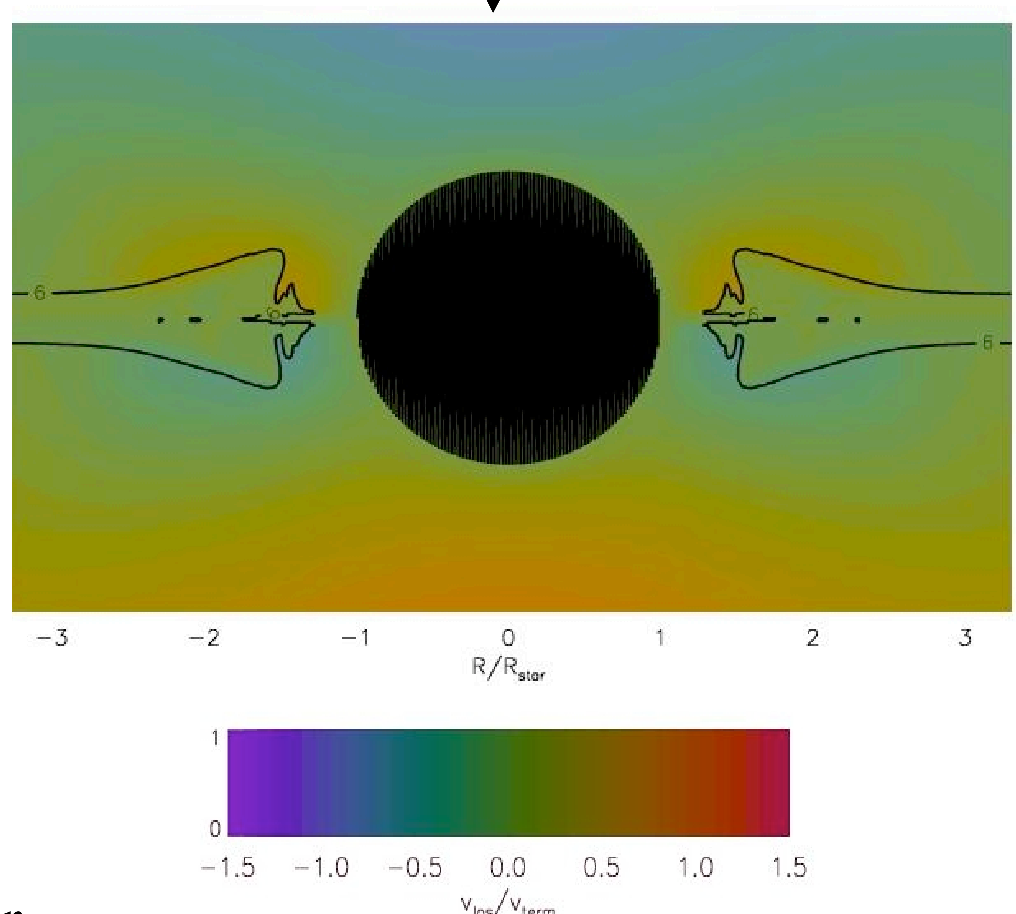


We thus synthesize line profiles for a range of viewing angles

Here we show 0°, looking down the magnetic axis

Color contours are now line-of-sight velocity; and the black contours enclose plasma with $T > 10^6$ K





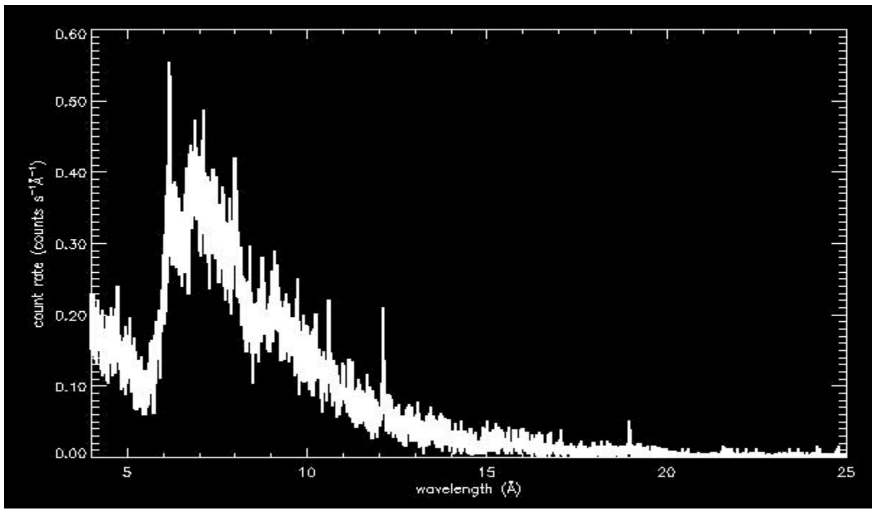
The profile is very narrow: see Mary Oksala’s poster for more

Magnetic OB stars, and normal B stars

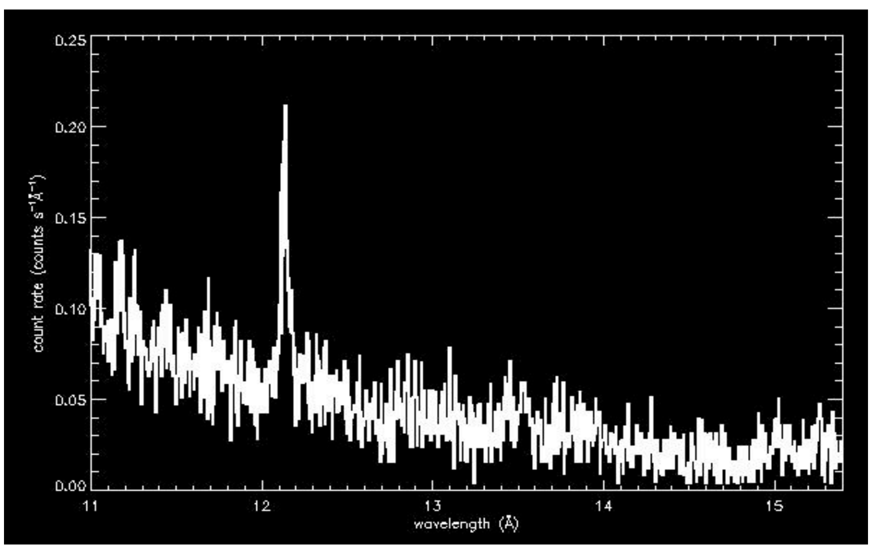
Magnetically channeled wind-shock models are promising (θ^1 Ori C, perhaps τ Sco): Schulz (AAS, 2003) has shown that O stars have these X-ray signatures for less than 1 million years on the main sequence

Normal B stars (like β Cru, B0.5 IV) have very soft X-ray spectra and narrow lines: wind shocks if the X-ray wind isn't moving very fast? Magnetically channeled wind shocks if the shocks aren't very strong? Dynamo-driven coronae if our understanding of dynamos is incomplete…

Then there are some extreme cases, like the Be star γ Cas

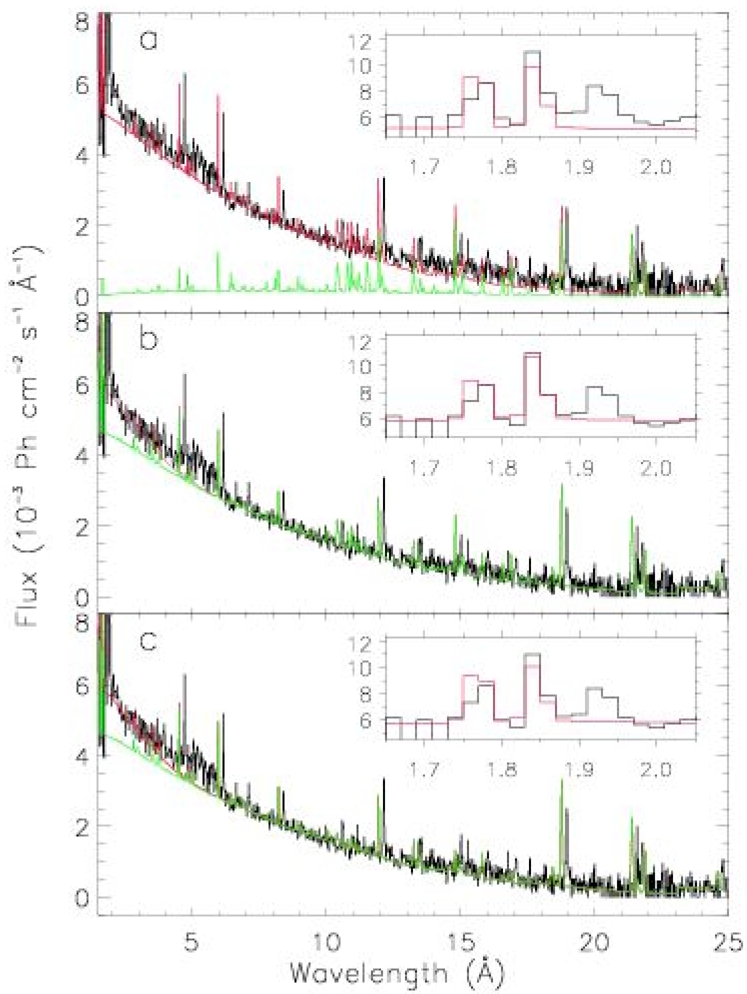


DEM with peak at kT=12 keV



Ne X Ly α line is broadened (HWHM ~ 500 km s^{-1})

γ Cas: HETGS spectrum with iron complex



Possibly extreme magnetic activity associated with Be star disk

Other "extreme" hot stars

Wolf-Rayet stars: metal enriched, very evolved, extremely dense winds: are actually **very weak X-ray** sources, probably due to very large wind continuum opacity

η **Carina**: possibly the most luminous star in the galaxy: *Chandra* (Corcoran et al.) and *XMM* (Leutenegger et al.) grating spectroscopy:

central star has very hard emission;

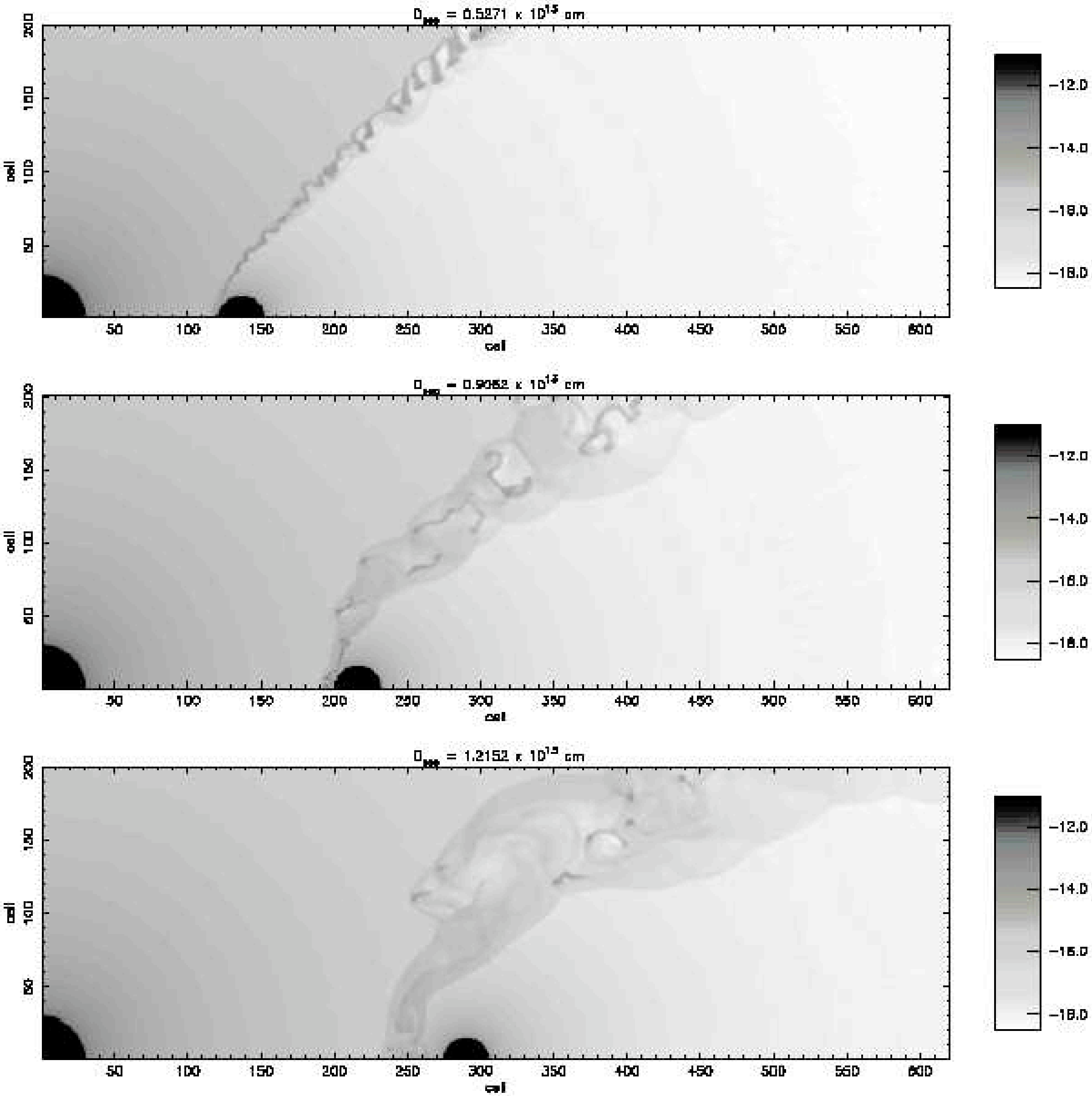
lines are not very broad;

absorption and Fe fluorescence;

large *f/i* ratios.

Consistent with **colliding wind binary** X-ray emission

Models of colliding winds show complex hydro structure

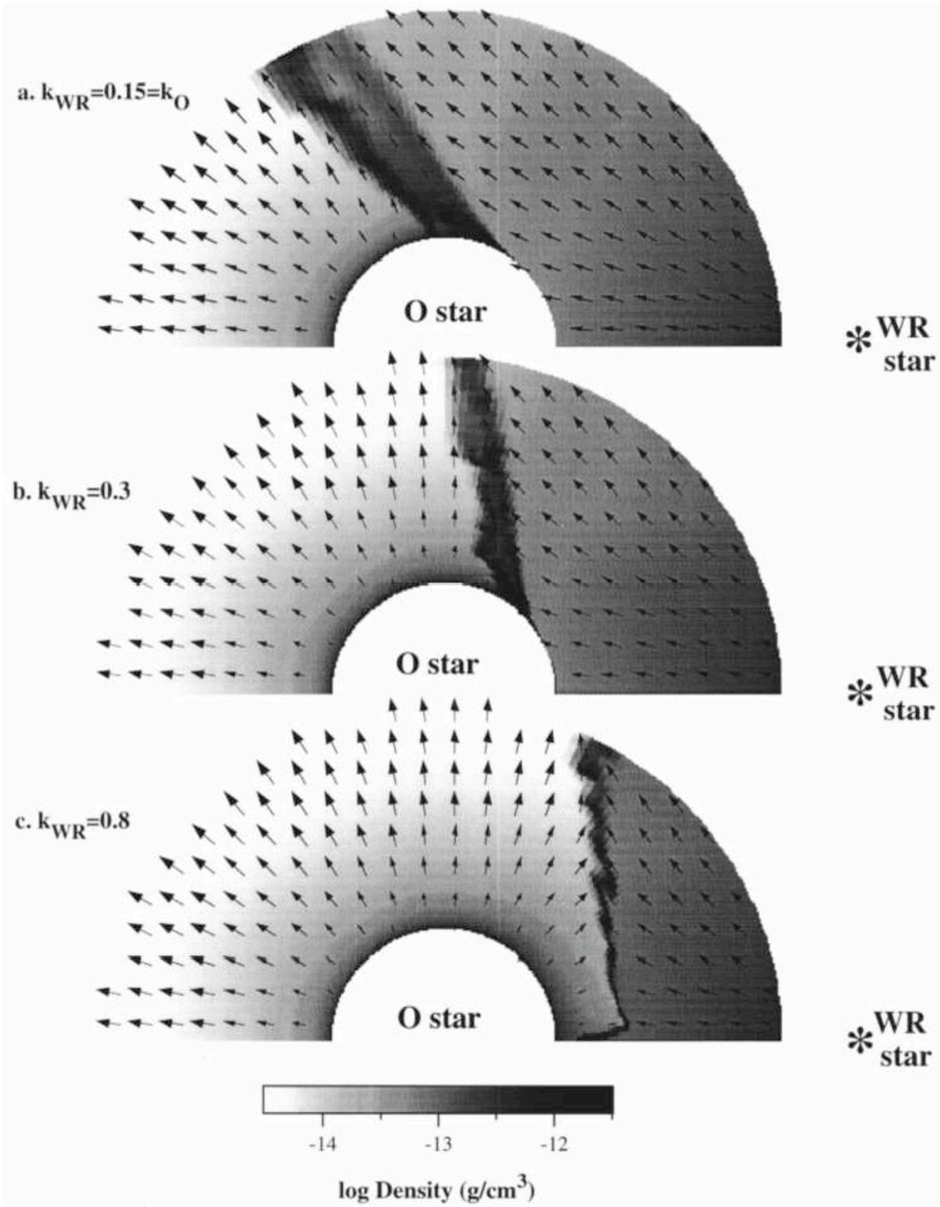


Models of *i* Ori (J. Pittard):

Line profiles have the potential to diagnose kinematics, shock physics

There’s phase dependence

Absorption and fluorescence from cold, post-shock material

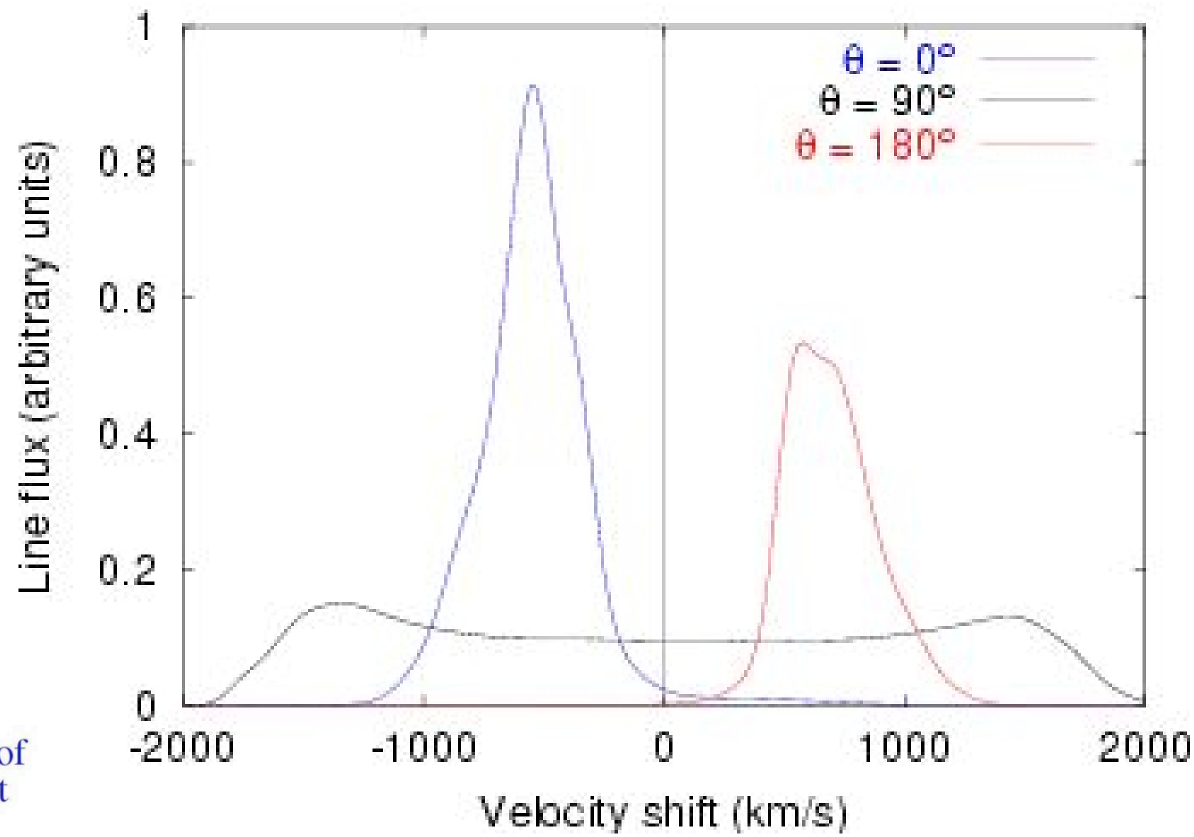


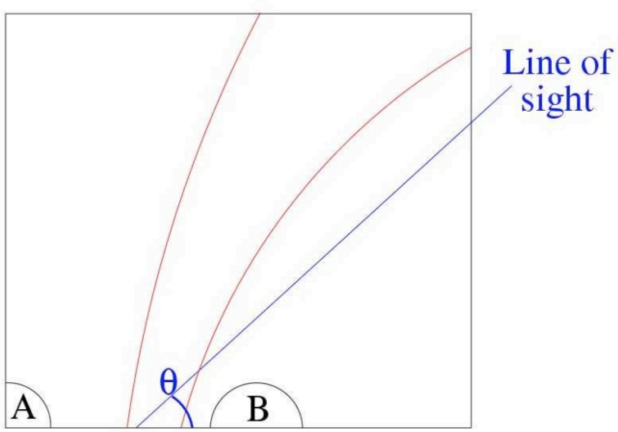
Radiative Braking (influence of one star's radiation on the other star's wind) is expected in some systems (figure from Gayley, Owocki, & Cranmer 1997)

High-resolution spectroscopy of line emission can test this.

Line profile models by D. Henley, I. Stevens (Birmingham, UK)

Basic test of the simplest aspects of wind-wind collision models





Results should be in soon: WR 140, η Car (to be observed at periastron this month)

Interacting Wind Sources

Line profile analysis as a function of orbital phase can test the shock physics and the geometry, kinematics, and hydrodynamics of some of the most extreme sources in the galaxy

Combining this information with other X-ray diagnostics (*f*/*i* ratios, absorption and fluorescence, DEM analysis) will be very useful

Conclusions

• There is a relatively wide variety of line profile morphologies seen in *Chandra* and *XMM* observations of OB stars

• By combining line profile analysis with other diagnostics, it is becoming clear that a surprising variety of high-energy physical processes are occurring in early-type stars

• ***Constellation-X***:

High(er)-resolution line profile analysis of short-wavelength lines

Ionization structure of Fe complex

Much better S/N and time coverage (X-ray line profile variability?)

Vast increases in the number of stars studied (is there a strong Malmquist bias in the current data?)